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INVESTIGATION OF FLASH X-RAY TECHNIQUES IN SOIL DYNAMICS AND INTERACTION PROBLEMS

Warren J. Baker and Frank J. Janza

The Eric H. Wang Civil Engineering Research Facility
University of New Mexico
Albuquerque, New Mexico
Contract AF29(601)-6002

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August 1966

AIR FORCE WEAPONS LABORATORY
Research and Technology Division
Air Force Systems Command
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FOREWORD

This report was prepared by The Eric H. Wang Civil Engineering Research Facility, University of New Mexico, Albuquerque, New Mexico, under Contract AF29(601)-6002. The research was performed under Program Element 7.60.06.01.D, Project 5710, Subtask 13.166, and was funded by the Defense Atomic Support Agency (DASA).

Inclusive dates of research were March 1963 through February 1966. The report was submitted 20 July 1966 by the AFWL Project Officer, Major John P. Thomas, (WLDC).

The authors are grateful to Mr. Harold R. J. Walsh formerly of the Air Force Weapons Laboratory (AFWL, WLDC), for early interest in flash X-ray techniques and suggestions during the first stages of this work; to Major John P. Thomas, AFWL (WLDC), for aid while monitoring this project and for assistance during evaluation, proof-testing, and repairing of equipment; and to our colleagues at The Eric H. Wang Civil Engineering Research Facility (CERF) as follows: Dr. George E. Triandafilidis, Research Engineer, for assistance in planning programs for use of X rays in soil dynamics; Mr. Ansel Dickinson, Research Assistant Engineer, for assistance with the flash X-ray equipment; Messrs. Fred Zwirner and Clyde Rogers, technicians, for their work and suggestions during the project; and Dr. Eugene M. Zwoyer, Director, for his continued interest in seeing that every possible avenue was explored for the success of the flash X-ray studies in soil dynamics.

This report has been reviewed and is approved.

John P. Thomas

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ABSTRACT

This research was conducted to assess the utility of flash X-ray techniques in soil dynamics studies. Areas where these techniques should be successful, their limitations, and the type of information to be expected from them are discussed. Static and dynamic tests were conducted on soil samples of various thicknesses and densities, and on buried structures of various dimensions using the Zenith Radio Research Corporation Model 1454 Flash X-Ray System. Initial tests defined the proper techniques to record pictures under optimum conditions of exposure, scatter elimination, and sample size and density. Final tests showed that qualitative information could be collected on certain loose soils and that interaction problems could be designed to yield large deformations. Soil thicknesses of over 5 inches could not be penetrated satisfactorily by the Zenith Flash X-Ray System. However, recent preliminary tests (June 1965) with a 300-kv Field Emission Corporation field-emission X ray were made through 8 inches of soil. It was concluded (1) that direct recording on film instead of using an image intensifier provides better contrast, field of view, and resolution, but problems of intensity and film transportation are great; (2) that more refined techniques and improvements are needed to collect quantitative information; and (3) that the inadequate state-of-the-art in multiple flash X rays at the time of this research limited their utility in soil dynamics. Further investigation is recommended based on recent and significant developments in field-emission X-ray-type systems.

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

ABBREVIATIONS AND SYMBOLS

a.	ampere(s)
ac	alternating current
b	distance to first maximums
cm	centimeter(s)
cm^2/gr	square centimeter(s) per gram
Co^{60}	cobalt 60
cps	cycles per second
d	diameter of X-ray target spot
db	decibel(s)
dc	direct current
D	density of silt
e	void ratio of soil samples
fps	feet per second
fr/sec	pictures or frame rate per second
ft	foot(feet)
gr/cm^3	gram(s) per cubic centimeter
G_1	gain of 9-inch image intensifier
G_2	gain of two-stage image intensifier
HV	high voltage
in./in.	inch(es) per inch(es)
$I_t(\nu)$	radiation intensity (function of frequency) after beam has passed through body
$I_o(\nu)$	radiation intensity (function of frequency) incident to body
kc	kilocycle(s)
kv	kilovolt(s)
kvp	kilovolt potential
Kev	kilo-electron volt(s)

ABBREVIATIONS AND SYMBOLS (Cont'd)

ℓ	distance from X-ray spot to test object
ℓp/mm	line pairs per millimeter; figure of merit
ma	milliampere(s)
mil(s)	milliinch(es)
mm	millimeter(s)
mr	milliroentgen(s)
msec	millisecond(s)
Mev	million-electron volts
nsec	nanosecond(s)
p	photocell output from X-ray print in 0.1 microamperes
pcf	pounds per cubic foot
pps	pulse(s) per second
prf	pulse-repetition frequency
s	logarithmic ratio of photometrically measured light intensity before and after passage of light through photographic layer
s/ℓ	magnification (or reduction) factor
s_1	distance of photographic film behind test object
s_2	distance of image-intensifier screen behind test object
sync.	synchronization
SiO_2	(silicon dioxide) silica
S-I	source to image
t	thickness of body to be penetrated
t_0	time zero
ϵ	penumbra degradation, unit of length
μf	microfarad(s)
μsec	microsecond(s), (10^{-6} sec)
μ/ρ	mass-absorption coefficient of body

ABBREVIATIONS AND SYMBOLS (Cont'd)

ν frequency

ρ mass density of body

SECTION I

INTRODUCTION

1. Purpose of Report.

This report reviews the history of X-ray studies in soil dynamics at the Eric H. Wang Civil Engineering Research Facility (CERF) since early 1963; presents data obtained from these studies; points out the difficulties of applying flash X-ray techniques to soil dynamics; and recommends areas of further study and development that may result in an effective flash X-ray analysis and measurement technique in soil dynamics.

2. Role of X Rays in Soil Studies.

X rays have been used occasionally in soil mechanics to monitor soil-density changes under load or as a result of various placement techniques (Refs. 1, 2). Tracking the motion of small, X-ray-opaque pellets in the soil has also been an important application (Refs. 2, 3, 4, 5).

Three unique features of the X-ray technique make it a desirable method of measurement in soil. First, it is a whole-field technique which gives a full picture of the events in an area that can be photographed. In comparison, gages placed in soil to measure soil or structure motion can give, essentially, only point information. X rays may be used to define the progression and shapes of failure planes, a decided advantage over other instrumentation techniques. Second, the penetration of X rays through a soil sample, resulting in the exposure on recording film, is a direct function of the soil density and is a convenient way to record density changes as stresses are developed in a soil mass. Third, very small, opaque pellets (slightly larger than soil grains) embedded in a soil mass can be tracked when subjected to stress changes. Thus, many displacement measurements of soil can be taken in the field of view by setting up an array of pellets. The measurements may be taken without disturbance of the soil by internal instrumentation since the X-ray source and recording medium are outside of the soil sample. Generally, soil-placed gages will affect the surrounding soil motions which occur when stress is applied to the soil (Refs. 6, 7, 8). Factors such as modulus mismatch, acoustic impedance mismatch, and arching will influence the readings from an embedded gage. Adequate corrections of these factors are usually difficult to apply.

The X-ray technique used in the study of soil dynamics has not yet produced the expected results (Ref. 9). Repetition rate, duration, and intensity of X rays have not been developed to a point where the information on a dynamic record is adequate for analysis of the changes in the soil as a stress wave passes through it. Minimizing the scattering of X rays in soil also requires extensive investigation.

3. Review of Static Work.

In 1929 Gerber (Ref. 3) used X rays to determine the overall displacements in a soil sample when a failure load is applied. He was able to track 3-mm (millimeter) lead pellets in sand loaded by a 3-inch steel plate. The thickness of the sample was 8 inches, the maximum thickness that could be effectively penetrated. The photographs were not clear enough to be reproduced, and some of the pellets did not show on the radiographs.

The next major step in the use of the X-ray technique, with a continuous source system, did not occur until 1949 when Davis and Woodward (Ref. 2) investigated a two-dimensional, footing-failure problem. Their results were very encouraging; density changes and incipient failure planes and patterns were easily seen beneath the footing. Lead bird shot was placed in a mesh below the footing, and displacements of the shot were measurable at depths of three footing widths. A dense wedge which developed directly beneath the footing was also easily detected. Their study employed direct exposure of 11- by 17-inch X-ray film, as well as a fluorescent screen placed behind the soil sample, and was photographed with a 35-mm camera. The soil samples were moderately well-compacted sands, 3.0 to 4.5 inches thick. The latter dimension was the maximum thickness that could be penetrated by their X-ray system.

In 1951 Berdan and Bernhard (Ref. 1) performed pilot studies on density measurements by X rays. In essence they took pictures before and after compaction of a soil sample. A granular beach sand and a cohesive silt were used; and the samples were 3.11 inches thick. The X-ray equipment was a Westinghouse Industrial Unit with a 150-kilovolt (kv) rating. The X-ray exposure--at 60 kv, 30 ma (milliamperes), and a 48-inch focal length--was 9 minutes and produced a readable X-ray film placed behind the soil sample. The authors demonstrated that the plot of soil density versus X-ray print density follows a straight-line law of the form

$$D = 104.5 - 1.16p \qquad (1)$$

where

D = soil density of the Hagerstown silt soil sample in percentage (100-percent soil density represents the maximum compaction within the sample which could be obtained by tamping), and

p = photocell output from X-ray print in 0.1 microamperes.

The film densities were measured by using conventional densitometer techniques. It was possible to plot isopycs (contours of equal density) throughout the sample. Large density changes (10 to 15 percent) did occur. However, the *minimum* density change that could be detected was not determined. They also embedded a pressure cell in the soil which was then compacted. The decreased density in an area below the cell was obvious from the radiographs.

More recently Roscoe et al. (Ref. 4) used a continuous X-ray technique to determine strains in sand. This study was conducted in a model earth-pressure apparatus (Ref. 5) to determine the state of stress and strain behind a vertical wall structure as the structure was rotated from the surface into the soil mass. The apparatus had glass walls 6 inches apart, and X-ray film was placed in a cassette directly behind the sample. The equipment was a continuous industrial-type Müller M. G. 150 X-ray machine with a maximum rating of 8 ma at 150 kv with a 1.5-mm focal spot. The sand was used in a dense state (void ratio, e = 0.55), and adequate pictures were obtained with a source current of 8 ma at 130 kv and an exposure time of 4 minutes. Displacements of lead shot, 2.5 mm in diameter and placed in a fine mesh behind the wall structure, were tracked with satisfactory results. Shear planes and planes of incipient failure could be detected from the dilatancy which took place on these planes.

Arthur et al. (Ref. 5) were interested in studying plane-strain problems which required that the apparatus walls be rigid, have a low coefficient of friction, and be transparent to X rays. Designing walls with these characteristics is difficult when the X-ray flux and exposure time are limited, as in a dynamic situation. However, the information presented in References 4 and 5 prove rather convincingly that for static work in soil the X-ray technique is a very useful means of instrumentation.

SECTION II

TECHNIQUES IN SOIL DYNAMICS

The major difference between X-ray studies in static and dynamic soil tests is the amount of time available during the test to pass sufficient X rays through the sample to adequately expose the recording film.

When the tests are dynamic, two types of available X-ray machines may be used. The first has a multiple flash X-ray source with a pulse width of usually less than 1 microsecond (μsec). The duration of the pulse is short enough to essentially stop the motion in a soil sample loaded dynamically. The number of pictures or frame rate per second (fr/sec) and the time lapse between pictures depend on the number of voltage pulses applied to the X-ray tube, or the pulse-repetition frequency (prf). The pictures are recorded with a high-speed motion picture camera after the shadowgraph from the transmitted X rays has been transformed and converted to visible light through an X-ray image intensifier. The transmitted X rays can be used to expose X-ray film directly without an image intensifier and a high-speed motion picture camera. If the film is held stationary, the record is in the form of a series of multiple exposures on one frame. The film on a drum can be rotated at a convenient rate to provide multiple frames with a single exposure. The time history in all cases is provided by the pulse-repetition frequency.

The second machine has a constant-potential X-ray source which produces a continuous flow of X rays through the soil sample. By rotating a drum with the film on it, a streak photograph of buried objects may be obtained. The deviation of this streak from its original path is directly related to the displacement of the object in the soil. Since the drum velocity provides the time base for this record, the slope of the streak is directly related to the object velocity.

The use of radioactive pellets (gamma-ray emitters) embedded in soil has also been given some attention (Refs. 9, 10). In most cases detection of the motion of the radioactive pellet is the means of obtaining information. However, it may be possible to use the irradiating flux from a particularly radioactive isotope in the same manner as the flux from X-ray machines is used. This technique would maintain the whole-field characteristics of X rays and permit the use of thick soil samples if the radioactive isotope were buried in the soil sample behind the lead pellets (Fig. 1). The radioactive isotope must be placed so that it does not affect the accurate measurement of the displacement of lead pellets during a

dynamic soil test. The intensity of the gamma-ray flux is increased in this technique by greatly reducing geometric attenuation (Fig. 1).

Some pronounced differences between the pulsed X-ray source and the gamma-ray source require investigation. For example, the radiation quality and intensity of a radioactive source are determined by the amount and nature of the emitter, and they cannot be changed with the same ease as an X-ray system. The gamma rays from cobalt 60 $\left(Co^{60}\right)$ have relatively great penetrating power and can be used to radiograph sections of 8-inch thick steel (or 24 inches of aluminum). Such penetrations require long-time exposures. The radioactive pellets are essentially isotropic point-source radiators, and about one-hundredth of the radiated flux can be utilized. Further studies are necessary to determine the gamma-ray intensity versus exposure times required for dynamic soil measurements. The spectral energy distribution of Co^{60}, for example, is considerably different than for a 1-Mev (million-electron volt) X-ray machine. The X rays are given off in a continuum of energies from 1 Mev to 0, and the gamma rays are emitted as two spectral lines with energies of 1.3 and 1.2 Mev.

Preliminary investigation of the technique presented in Figure 1 indicates its major problems, which overshadow its advantages: (1) developing a simple method for obtaining frames of data from the continuous gamma-ray source, (2) overcoming hazards of handling and positioning radioactive isotopes, and (3) obtaining sufficient gamma rays from the amount of radioactive material which can be placed in the soil without changing its characteristics.

Since there has been very little research on application of radioactive pellets to soil measurements, new designs and techniques will have to be tested. It is likely that development of an adequate measurement system would require from two to three years.

Embedded radioactive isotopes may be used in two other ways which are not, however, whole-field techniques. The first is simply to embed the isotope in the soil bin and detect its motion with scintillating crystal detectors (Ref. 9).

The resolution capabilities of this first technique raise a serious question. For example, will it be possible to reduce the field of view of the scintillating detectors to prevent cross detection by shielding so that displacements of less than 5 mils (milliinches) can be resolved? Actually, displacements as small as 1 mil will need to be resolved for evaluation tests of such a soil measurement system.

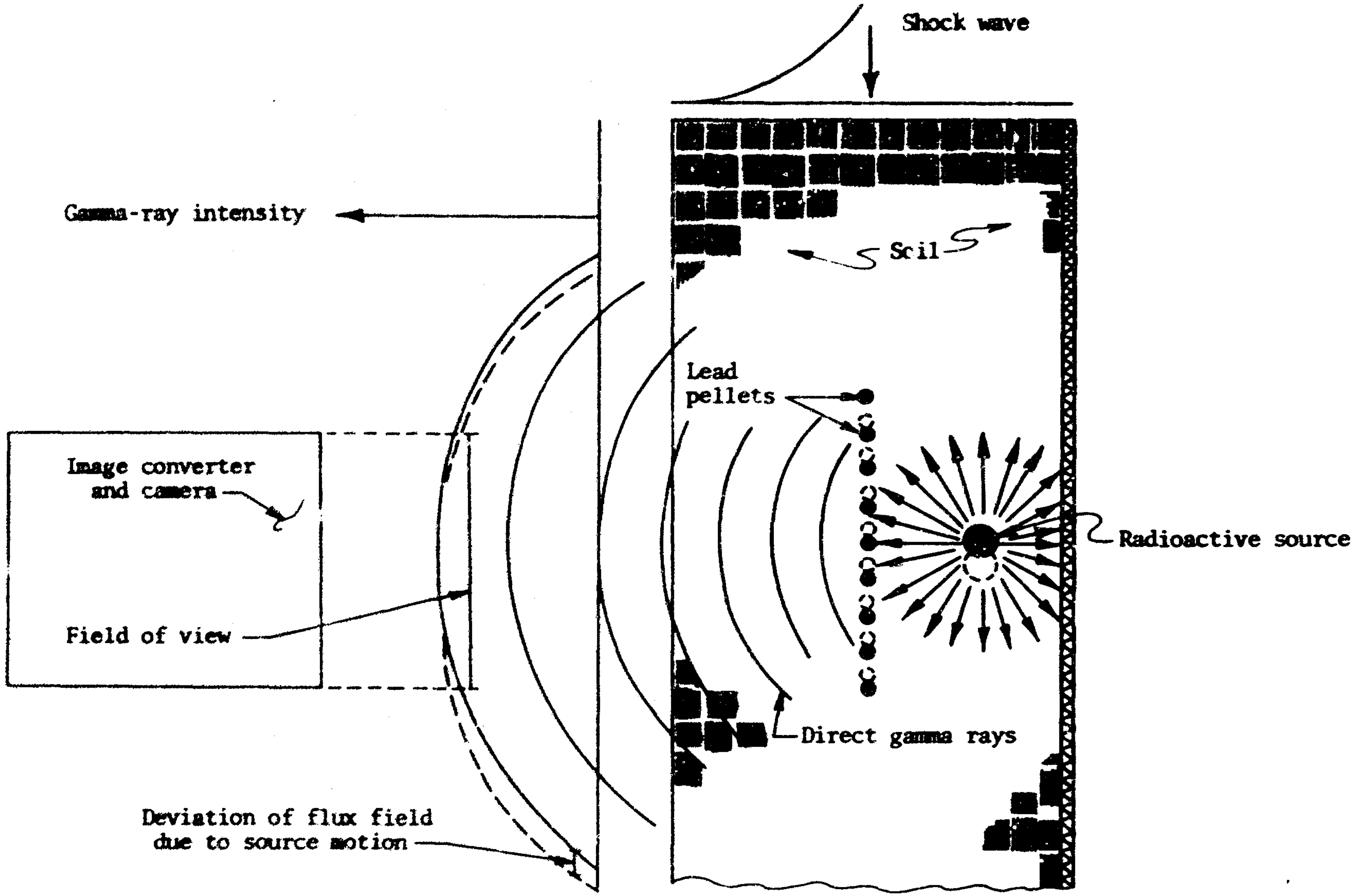


Figure 1. Buried radioactive pellets

The second approach is to apply the Mossbauer effect, which is a resonance absorption of gamma rays where both the emitting and absorbing nuclei of isotopes are prevented from recoiling. Mossbauer demonstrated that the technique gave interesting Doppler effects when the source and absorber were in relative motion (Ref. 11). Further study of the Doppler effects indicate the possibility of the emitter being buried in a soil sample while the absorber is held stationary with detection equipment outside of the sample. The result would be an accurate time record of the motion of the emitter embedded in the soil.

The main advantage (which requires experimental verification) of the use of embedded radioactive isotopes is the accuracy of the motion measurements that could be made without harmful disturbance of the soil. The disadvantage is that both techniques are a point-by-point detecting system and may require crowding several scintillators around a soil sample to gather sufficient information. These techniques might be applied successfully in tests when two or three motion measurements are required in severe shock-temperature environments where displacement, velocity, or acceleration gages do not work.

In selection of an X-ray system some priorities based on penetrability, practicability, and availability have developed. After discussion with experts in the application of X rays to nondestructive testing and fields closely associated with soil dynamics, priorities in the following order are suggested:

1. Multiple-flash, field-emission-type X-ray system.* (This selection is based on availability and capability of penetrating 8 inches of Ottawa sand. For greater soil penetration, the Betatron or the linear accelerator should be investigated.)

2. Embedded radioactive isotopes used with scintillating crystal detectors. (Considerable developmental work and experimentation are required before a usable system would be available for dynamic soil measurements; however, the feasibility of such a system has been demonstrated for other applications with similar stringent requirements.)

3. Embedded radioactive isotopes in an arrangement to maintain the whole-field characteristics of X rays, or the application of the Mossbauer effect.

*The multiple-flash, field-emission-type X-ray system, with demonstrated capability in dynamic soil measurements, is a recent development (1965). At the beginning of this study (1963), the multiple-flash X-ray system using a hot cathode-type X-ray tube was the only available system.

(Both techniques require extensive development before a workable system would be available.)

Certain areas of research in soil dynamics are particularly suited to experiment with X-ray techniques, because displacements, density charges, and formation of shear or rupture planes as a function of time are important characteristics; and the formation of shear or rupture planes usually cannot be obtained conveniently with other techniques.

The changes in the *free field* as a stress wave passes through a soil sample may be studied with X rays. The motion of small lead pellets which appear opaque to X rays when embedded in soil samples 3 to 8 inches thick may be tracked on film with an appropriate time marker. However, information derived from X-ray records is limited by the effects of boundaries on samples only 3 to 8 inches thick, and boundary effects are serious when simulation of one-dimensional behavior at great depths is attempted. Displacement gages have been developed recently (Ref. 6) which are reliable for free-field measurements. By using gages in progressively larger samples, the effects of sample thickness may be detected. Consequently, *free-field* information derived from X-ray records is expected to be somewhat limited.

Laboratory experiments on *Direct Explosion Coupling, Cratering, and Underground Explosion Cavities* (Ref. 12) can be monitored using high-speed X-ray techniques. The X-ray records will provide information on the development of cavities, propagation of fractures in brittle materials, and the mechanism associated with cratering. The experiments are restricted by boundary conditions imposed by sample thickness limited by 3 to 8 inches. The type of information obtained in experiments with X rays, however, cannot be as completely obtained with other techniques.

The greatest advantage of the X-ray technique is found in experiments where *interaction between the soil and a structure* takes place. It is nearly impossible to adequately instrument such experiments with gages on the structure and in the soil so as to define the interaction.

Buried models taken to failure or subjected to large deformation are well suited to the X-ray technique. It should be possible to monitor with X rays the collapse and deformation mechanisms of lined and unlined tunnels of various shapes and the resulting soil deformation. Model footings taken to failure dynamically develop displacements and failures in the soil that are easily detectable by X ray.

In such cases the large motions that occur as a result of the loading event provide ideal conditions for the X-ray technique to produce information not normally available. The model footing is distinct from the surrounding soil, and its motions are generally visible. Failure planes and large pellet motions in the soil are also easy to detect with X rays.

Recently, interest has grown in the mechanics of projectile penetration into soil. This interest stems mainly from the desire to increase the coupling efficiency of nuclear weapons as well as to gather information and data for design of invulnerable (protective) structures below ground. A model projectile will provide a high contrast to the surrounding soil on a radiograph. Consequently, it is feasible to track the path of a model projectile and the soil changes as it penetrates various types of soil. Characteristics such as impact velocity, impact angle of incidence, soil properties, and projectile shape can be easily varied in laboratory tests; and the effects on projectile performance can be monitored with X rays.

An important feature in any laboratory test on large samples of soil is the effect of soil-container boundary conditions. Recording by X ray the motions near boundaries can be particularly effective since most soil-placed gages are unreliable near boundaries.

Great effort has been expended recently to develop soil-placed gages for dynamic use. Berdan and Bernhard (Ref. 1) showed that placement problems of buried pressure cells could be studied with X rays. The placement and response of gages used in soil dynamics are particularly important, and the development of an evaluation technique using X rays would be very worthwhile. The evaluation technique should be designed to assess the influence of the gage on the surrounding soil and to distinguish between the motions of the gage and the soil if the gage were not there.

SECTION III

FLASH X-RAY TECHNIQUES IN SOIL DYNAMICS

When flash X-ray studies in soil dynamics were first considered by CERF in 1963, it was difficult to provide comprehensive specifications for the test apparatus. The difficulty arose because great penetrating power was needed in very short time to record information. Proved flash X-ray equipment to provide this penetrating power in short bursts was not available, and some development was needed. Technology in flash X rays has advanced rapidly in the past two years, and studies at CERF indicate that specially prepared soil samples and buried test objects can be studied under dynamic conditions with flash X-ray equipment. The experience at CERF has been with a high-capability, single-source, multiple-flash X-ray system which is highly versatile, due to its modular-type construction, and easy to operate.

1. Time.

In dynamic events the time factor associated with sensing instruments means several things. Specifically, with a multiple-flash X-ray system, one is concerned with the duration of the X-ray pulse, the pulse-repetition rate, and the total time span over which X-ray pulses can be produced. The pulse duration must be short enough so that a still picture of the soil sample can be taken (without objectionable blurring) while a shock wave is traveling through the soil at high velocities, i.e., 800 to 2,500 feet per second (fps). Today X-ray technology can easily produce pulse widths from 18 nanoseconds (nsec) to 2 μsec.

2. X-Ray Intensity.

The most important requirement of a flash X-ray system for use in dynamic soil tests is the generation of flash X rays of high intensity. This radiation intensity or flux emanating from almost a point source is subject to geometric attenuation as the X rays diverge from the source. In addition to geometric attenuation, the X rays are also subject to severe attenuation from mass absorption of radiation as they penetrate the soil sample. The geometric attenuation follows a simple inverse square law in a nonabsorbing homogeneous medium

$$\frac{I_1}{I_2} = \frac{d_2^2}{d_1^2} \qquad (2)$$

where

I_1, I_2 = radiation intensity at two points along the axis of divergence from the point source, and

d_1, d_2 = distances of two points along the axis of divergence from the point source.

To obtain a shadowgraph of that portion of the soil bin (approximately a 9-inch-diameter field of view) containing the embedded pellets, the X-ray source was moved about 18 inches from the front of the soil bin. The intensity was thus limited by the requirement for the field of view. By moving the X-ray source half way in, the intensity was increased and the field of view was decreased, each by a factor of 4.

The mass absorption was more severe since it is an exponential decay function which depends on the mass-absorption coefficient and thickness of the material. The following example of the mass absorption of a 6-inch, dense sample of 20-30 Ottawa sand (standard testing material) will delineate the problems in producing sufficiently intense X rays of short-pulse widths.

In Ottawa sand, a unit weight of 111 pounds per cubic foot (pcf)--1.775 grams per cubic centimeter (gr/cm^3)--represents a void ratio of 0.5. Ottawa sand is nearly 100 percent silica in the form of quartz, and a sample 6 inches thick represents 4 inches of solid quartz which must be penetrated. The mass attenuation of radiation follows the law

$$I_t(\nu) = I_o(\nu)e^{-\left[\mu(\nu)/\rho \times \rho t\right]} \qquad (3)$$

where

$I_t(\nu)$ = radiation intensity after beam has passed through body,

$I_o(\nu)$ = radiation intensity at frequency ν incident to body,

$\mu(\nu)/\rho$ = mass-absorption coefficient of body at frequency ν

ρ = mass density of body, and

t = thickness of body to be penetrated.

Mass-absorption coefficients for particular bodies can be calculated by weighting the mass-absorption coefficients of the elements in the body. The weight

factor is the atomic weight of the element divided by the atomic weight of the mixture making up the body. In this example it is convenient to calculate an X-ray intensity-reduction factor as

$$\frac{I_t(\nu)}{I_o(\nu)} = e^{-\left[\mu(\nu)/\rho \times \rho t\right]} \tag{4}$$

The value of $\mu(\nu)/\rho$ for SiO_2 at 150 Kev (kilo-electron volts) is nearly 0.14 cm^2/gr given by Bloedow (Ref. 9). The density of quartz is 2.65 gr/cm^3.

$$\frac{I_t}{I_o} = e^{-(0.14 \times 2.65)(4)(2.54)}$$

$$= e^{-3.77}$$

$$= 0.023$$

Thus, nearly 98 percent of the X-ray flux incident on a 6-inch sample of dense Ottawa sand is attenuated due to a mass absorption of the sand. Five inches of Ottawa sand would attenuate about 95 percent of the X rays; and 4 inches would attenuate about 92 percent.

Excluding the absorption edges, the mass-absorption coefficient generally decreases as the X-ray energy in electron volts increases. High-potential X-ray systems will produce high-intensity X rays of short wavelengths which have high-penetrating power. On the other hand, pictures taken with short-wavelength X rays do not have high contrast like those taken with long-wavelength X rays. Hence high-penetrating power is gained at the expense of contrast.

3. Resolution.

Resolution in X-ray records limits the quantitative information to be gathered. By using specially prepared soil samples and test objects, valuable information about dynamic behavior can be collected even if investigation is limited to large displacements. The minimum peak-particle displacements that might be effectively studied with X rays are displacements of 0.15 to 0.25 inch (or 150 to 250 mils). To determine the minimum detectable displacement, it will be assumed for purposes of calculation that the peak-particle displacement decays linearly in 10 milliseconds (msec). It seems valid to require that a measurable change in displacement be recorded at least every 1 msec. This means that particle

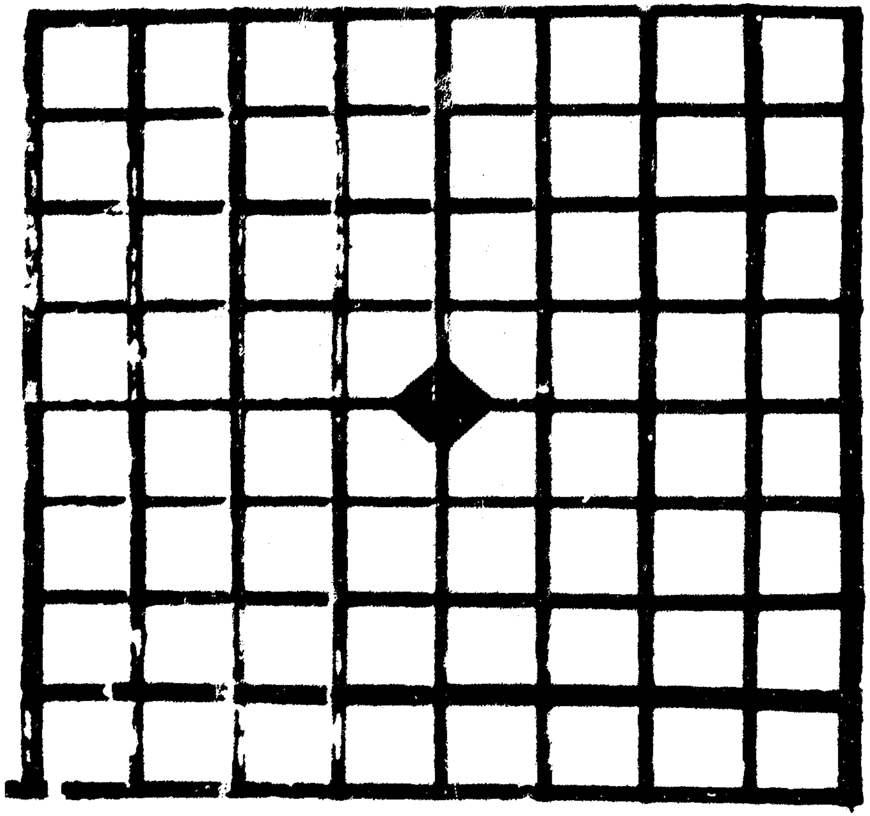
displacements between pulses should be resolvable to at least 33 percent in the interval (about 5 to 8 mils) so that the 15- to 25-mil change in displacement can be readily measured.

The minimum size of the lead pellets to be tracked should be 4 mm (158 mils) in diameter. This is slightly more than three times the maximum grain size of the Ottawa sand used in experimental work. No objectionable effects should result from this size pellet since the dimension in the direction of load application is quite small with respect to the length of the loading pulse. Bloedow (Ref. 9) showed (from a one-dimensional wave-propagation analysis) that the motion of the pellet becomes that of the surrounding soil very rapidly. Actually the effect of the pellet is less than indicated from one-dimensional theory since propagations and reflections occur in three dimensions in the pellet.

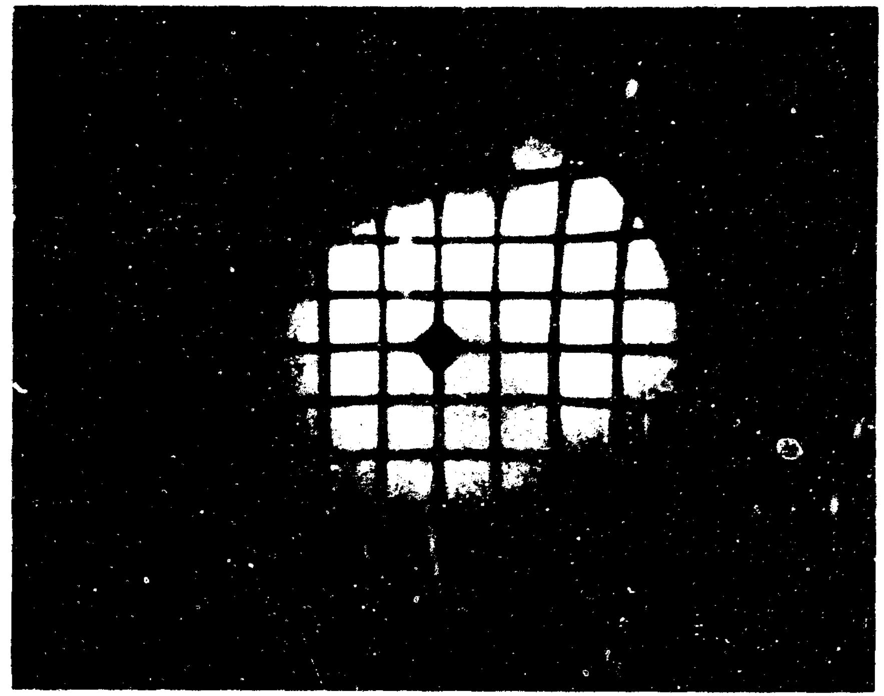
4. Field of View.

The size of the field of view is dictated by the particular experiment. It is important to keep the field of view to a minimum to better control the various kinds of geometric distortion and scatter for higher radiographic sensitivity. In the experiments with model footings, lined and unlined cavities, explosion cratering, and instrumentation evaluation (mentioned in Sec. II), the field of view cannot be reduced below certain minimums. For example, in the [illegible] modal failure of model footings resting on sand, a footing 1 inch wide will fail in a different manner than a footing 4 inches wide. It is also apparent that the failure mode of buried cylinders can change drastically for the same diameter-to-thickness ratio if the dimensions of the cylinder are very small. Many of the gages in dynamic soil testing have a maximum dimension that ranges from 1 to 8 inches. The area of interest above model structures, for which arching studies have been made, is nearly 8 square inches. Consequently, a very large field of view is desirable; anything smaller than 8 inches in diameter could seriously hamper the scope of studies in soil dynamics and soil-structure interaction.

The field of view must not be distorted dimensionally beyond correction. In fact, any dimensional distortion makes data acquisition somewhat inconvenient. In particular tests where density changes and failure planes are of primary interest, the field of view should maintain a nearly uniform intensity (brightness or film density). Where image intensifiers are used, the inherent vignetting (Fig. 2) is very noticeable, and steps may be taken to optically reverse this effect to obtain a nearly uniform background intensity.



(a) Input



(b) Output

Figure 2. Vignetting and dimension distortion in image intensifier

5. Material Properties.

It is desirable to study various soils from dry sand to wet clay, with grain sizes from 0.6 to 1.2 mm and 0.0002 to 0.002 mm, respectively, and with mineral contents from quartz to kaolinite clay. The dynamic response of soil is generally attributed to the constitutive relationships exhibited by a particular soil. A dense, uniformly graded sand may exhibit a one-dimensional secant modulus of 40,000 psi at a stress level of 100 psi, while a soft clay could easily have a modulus of 4,000 psi. The density of the sand may be as high as 120 pcf, and that of the clay as low as 80 pcf. In a dynamic soil test on a column of soil 3 feet high the surface will displace 0.1 inch if the material is dense sand, and 1 inch if the material is soft clay. The stress wave velocities at 100 psi in dense sand and soft clay will be about 1,300 fps for the sand, and 500 fps for the clay; and typical peak-particle velocities will range from 2.5 fps for the sand to 12.5 fps for the clay. Thus, depending on the capabilities of the X-ray equipment, a wide variety of soil types can be studied. If the resolution and penetration factors of the X-ray system are low and if adequate X-ray penetration is to occur, the selected soil must be the softer, less dense material, or a thinner sample has to be used.

6. Boundary Conditions.

The boundary conditions of concern are those at the soil-container walls. The walls create a friction effect in the soil which carries shear stresses normally carried by the soil. The stresses developed at the wall are transmitted to the soil and influence the soil response. The extent of this influence depends on the magnitude of the stresses developed at the boundary. The walls must be nearly rigid (and maintain a high transparency to X rays) to minimize the influence of three-dimensional deformations occurring in tests to simulate one-dimensional and two-dimensional behavior.

In studies of two-dimensional behavior, it is necessary to eliminate or evaluate the influence of the boundary perpendicular to the third dimension--sample thickness. If the third dimension is small in comparison to the two dimensions being studied, it will influence the two-dimensional response. Thus it is necessary to keep the thickness of the soil sample above a minimum value. What that minimum value is, will depend on the experiments; however, a sample thickness of less than 5 inches in some interaction studies may prohibit free-field experiments.

SECTION IV

RESULTS OF EXPERIMENTS WITH FLASH X-RAY SYSTEM

1. Zenith Multiple Flash X-Ray System.

The pilot tests with the Zenith Radio Research Corporation Model 1464 Multiple Flash X-Ray System were concerned with how well particular areas of soil dynamics and soil-structure interaction could be studied by multiple-flash X rays. The tests were hampered by frequent malfunction of the X-ray equipment. A great deal of operating time was spent in diagnostic testing to determine the causes of equipment failure. Consequently, a research program in soil dynamics has not been completed, but some insight into the possibilities of the X-ray technique has been gained. The Zenith equipment was developed for specific needs of CERF and has been used statically (for calibration purposes) and dynamically with sand and silt in rectangular cross-sectional containers. The dynamic inputs were developed with shock waves from a 45-foot vertical shock tube and with hydraulic rams. Figure 3 shows a typical test arrangement.

Figure 4 shows a schematic of the Zenith Model 1464 Multiple Flash X-ray System as used in a typical test arrangement. The multiple-flash X-ray system generates a series of eight 1-μsec pulses with a pulse-to-pulse time separation of 1,000 μsec. As the pulse-repetition frequency is lowered, the number of pulses per sequence increases. The high pulse-repetition frequency is possible for only a limited number of X-ray pulses because of the low rate of heat dissipation by the anode of the X-ray tube.

The specifications for the multiple-flash X-ray system are as follows:

X-ray tube accelerating voltage	50 to 150 kilovolts (kv) continuously adjustable
X-ray tube current	120 amperes (a.) at 100 kv
Pulse-power maximum	18 megawatts
Pulse energy	18 joules
X-ray pulse width	1 μsec
X-ray pulse shape	square
X-ray pulse rate	1 to 1,000 pulses per second (pps)

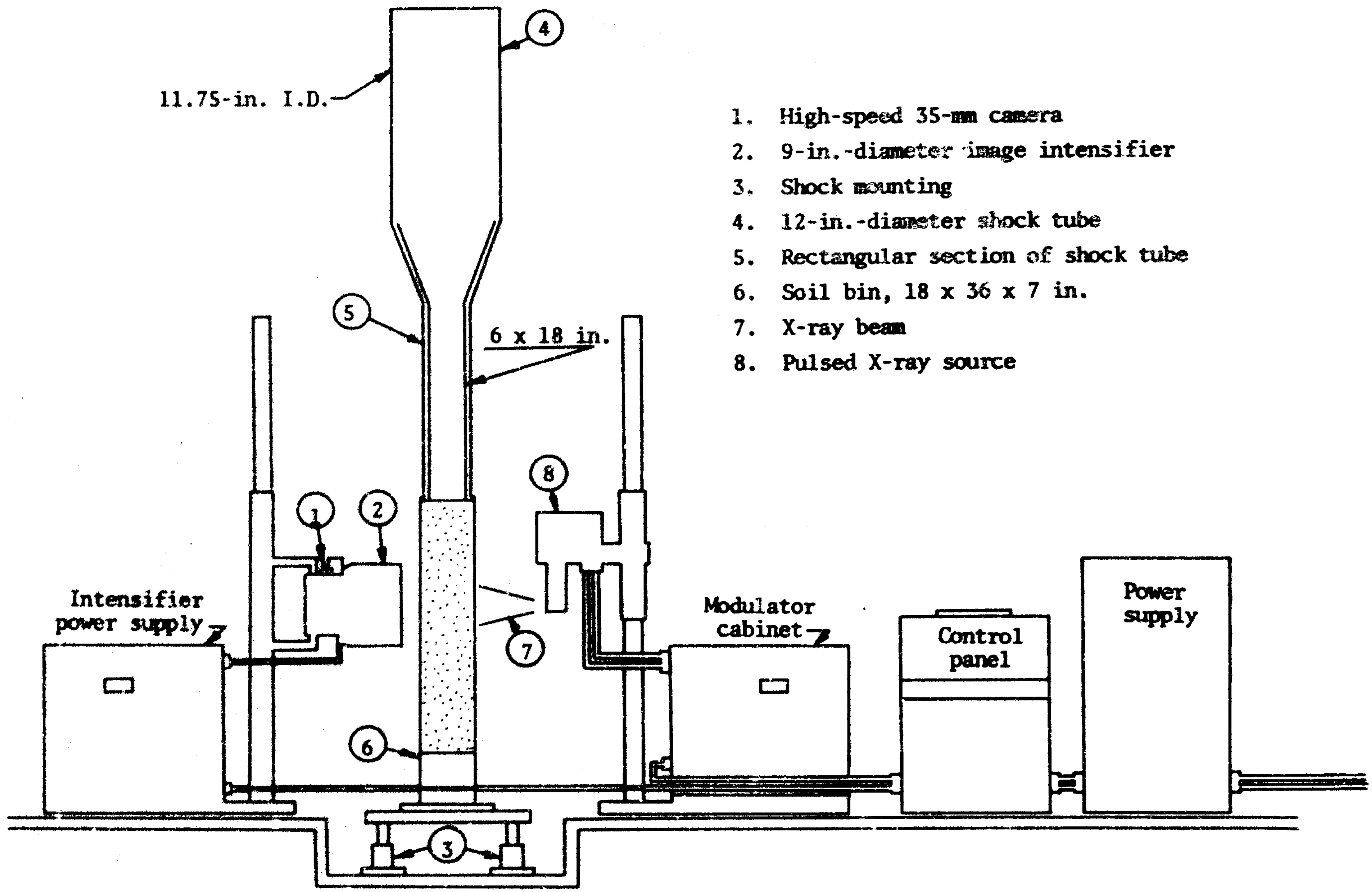


Figure 3. Flash X-ray test setup for soil dynamics studies

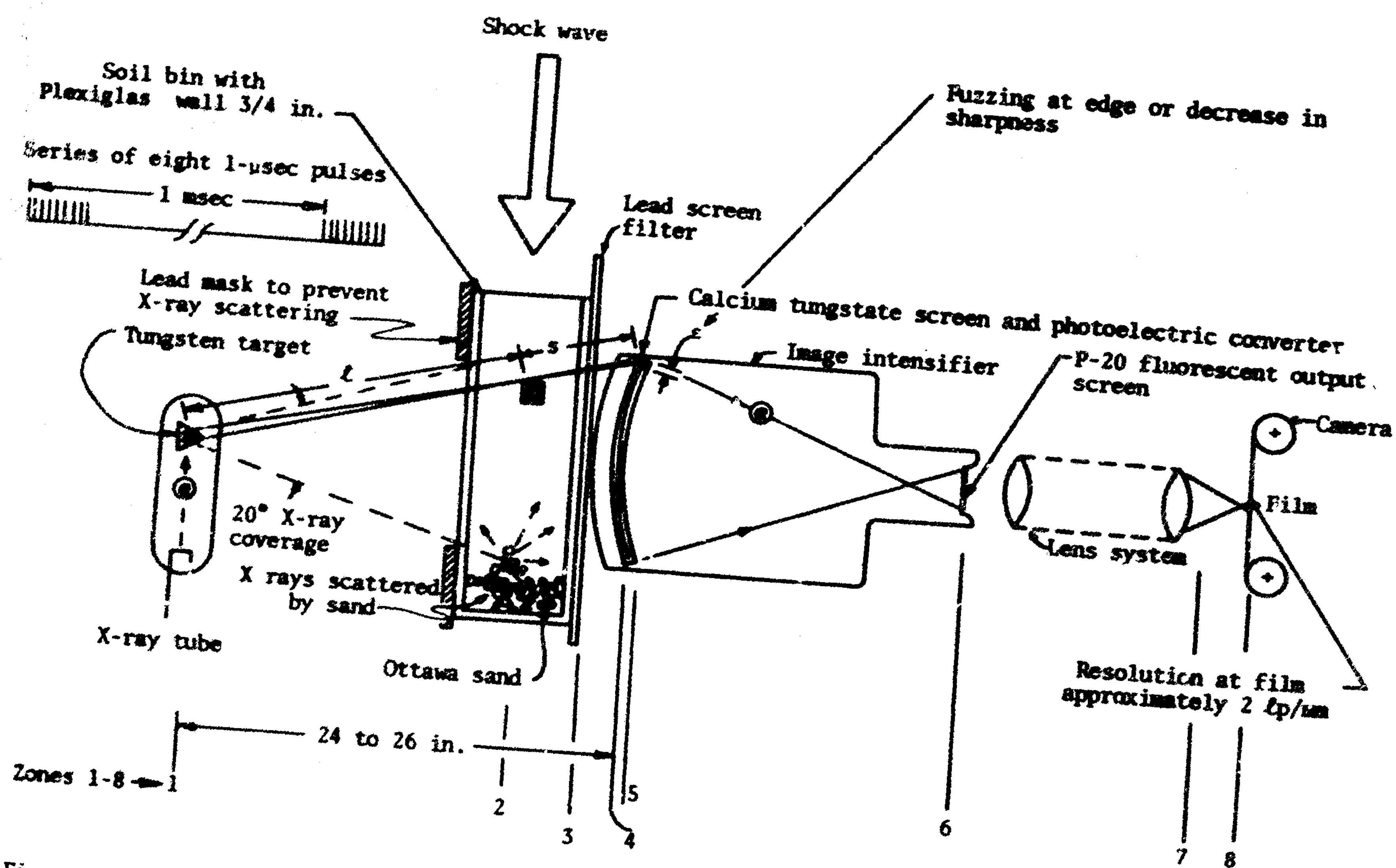


Figure 4. Multiple-flash X-ray system used to analyze shock-wave-induced pellet motion in Ottawa sand

Number of pulses in one sequence:

Pulse rate, pps	Maximum number, pulses
1,000	8
800	8
600	10
500	20
400	40
100	80
30	Continuous

Cone of radiation................20 degrees

Effective target spot size of 1- by 2-mm nominal X-ray beam*

Penetration.....................1 milliroentgen (mr) per μsec at 1 meter for 150 kv

Input power.....................208-220 volts, 60 cycles per second (cps), 3 phase, 150 a. during X-ray generation, 20 a. in ready condition

a. Advantages.

The advantages of the Zenith Model 1464 Multiple Flash X-Ray System over conventional X-ray systems in medical and industrial laboratories are

(1) The Zenith has stop-motion capability for transient events. (For example, a radiograph of a shock-wave front having a velocity of 3,000 fps is smeared out 36 mils by a 1-μsec X-ray pulse. A soil set in motion with a velocity of 100 fps by the shock wave has the radiograph of the motion smeared 1.2 mils by the 1-μsec X-ray pulse.)

(2) The Zenith provides a sequence of 8 pulses at the high pulse-repetition frequency of 1,000 pulses per second--actually a sampling rate--which allows resolving up to 500 cps, based on the sampling theorem of the spectrum of a pressure, displacement, velocity, or acceleration record. (The high-frequency components in a shock wave are well in excess of 500 cps and require a much higher sampling rate.)

*The electron beam sweeps over the tungsten target with a maximum excursion of 5 mm from target center. The 1- by 2-mm spot size permits X rays of subjects as close as 50 mm from the source without discernible loss of resolution.

(3) The Zenith has an 8-inch image-intensifier tube which converts X rays to electrons at the input screen and then converts the electrons to visible light at the output screen. The tube provides a gain of 3,000, thus the X-ray dosage can be lowered considerably. The information transformed to the visible region can then be coupled to a motion picture camera by optical methods. Being able to lower the X-ray-accelerating voltage, the image intensifier permits longer X-ray wavelengths to be generated and allows improving the contrast, particularly when the X-ray wavelength can be set at the radiation absorption edge of a material.

(4) The Zenith has a pulse-synchronization method that is initiated by a rotating disk, part of the camera assembly, thus providing a stable reference for triggering the X-ray tube.

(5) The Zenith X-ray tube costs about $5,000, and its life, according to the manufacturer's specifications, is approximately 10^6 pulses.

(6) The Zenith image intensifier allows the use of high-speed cameras for photographing pulse-by-pulse information over the same, or a fixed, field of view on 16- or 35-mm high-speed, high-contrast film which is readily available.

b. Disadvantages.

(1) The Zenith's upper pulse-repetition frequency of 1,000 pps is inadequate for recording the interaction of the leading edge of a fast-rising stress wave with a small pellet (4-mm diameter). (For example, an X-ray system generating 10^5 pps could provide two radiographs as the shock wave passes over the pellet.)

(2) The Zenith image intensifier (Rauland Corp. Model RA-R-6167) has considerable spherical distortion and vignetting. (This can be more than adequately corrected by using one of the new tube designs.)

(3) Even with the image intensifier the output is inadequate to sufficiently expose the film when 4 inches of sand has to be penetrated.

(4) The Zenith has too many variables in its X-ray system to provide ease of operation; for example, in X-ray dose, image-tube performance, camera synchronization, film exposure (between speeds), focus, and development control. (Some of these variables, however, are also probably inherent in other X-ray systems of similar design.)

(5) The Zenith is limited in resolution by the image intensifier and the optical system. The resolution at the output of the calcium tungstate surface

(Fig. 4) is around 2 line pairs per millimeter (ℓp/mm); at the output of the lens system it is about 1.5 ℓp/mm. Exposing the film directly with X rays increases the resolution where the extent of this increase is a function of (a) the distance of the object from the film, (b) the granularity of the film, (c) the X-ray target size, and (d) the density and scattering of the free-field medium.

2. Experimental Results with Zenith System.

a. Pertinent Characteristics of Equipment.

The Zenith Multiple Flash X-Ray System presented several problems that hampered any attempt at exact quantitative interpretation of the data. The X-ray intensity fluctuated sporadically from pulse to pulse in one sequence and showed up as density changes on the film or as an apparent density change in the soil sample. This is not serious unless the apparent density is confused with a density change caused by the shock wave. When the cause is not evident from the record, very little reliable information can be obtained about density.

The intensity of the X-ray beam in air at 1 meter from the source anode was 1 milliroentgen (mr). This flux was measured several times with accurate Landsverk dosimeters. The dosage from several pulses, as well as samples of 1 pulse at various times, was recorded. Occasionally, the dosimeter readings indicated less than 1 mr per pulse because of pulse fluctuation.

As the X-ray tube ages, an impedance mismatch between the driver transformer and the tube develops. As a result a reflected pulse from the anode travels back through the system because of change in the characteristic impedance of the tube. The reflected pulse at times recorded as high as 25 kv and is a possible source of equipment failure.

The image intensifier is 8 inches in diameter at the pickup screen. The image is intensified 3,000 times and focused on a screen about 1.5 inches in diameter. Inherent vignetting and dimension distortion (pin cushioning) are found in the older designs of electrically focused intensifier tubes. The extent to which vignetting and distortion occurred is shown in Figure 2. The decay of brightness along the radius shown in Figure 5 is more than 40 percent at the edge of the screen. These data indicate the middle four inches of the image intensifier are best suited for recording.

b. Procedure.

Experimentation with the equipment was necessary to determine the most efficient procedure to procure the best data from rectangular soil samples loaded

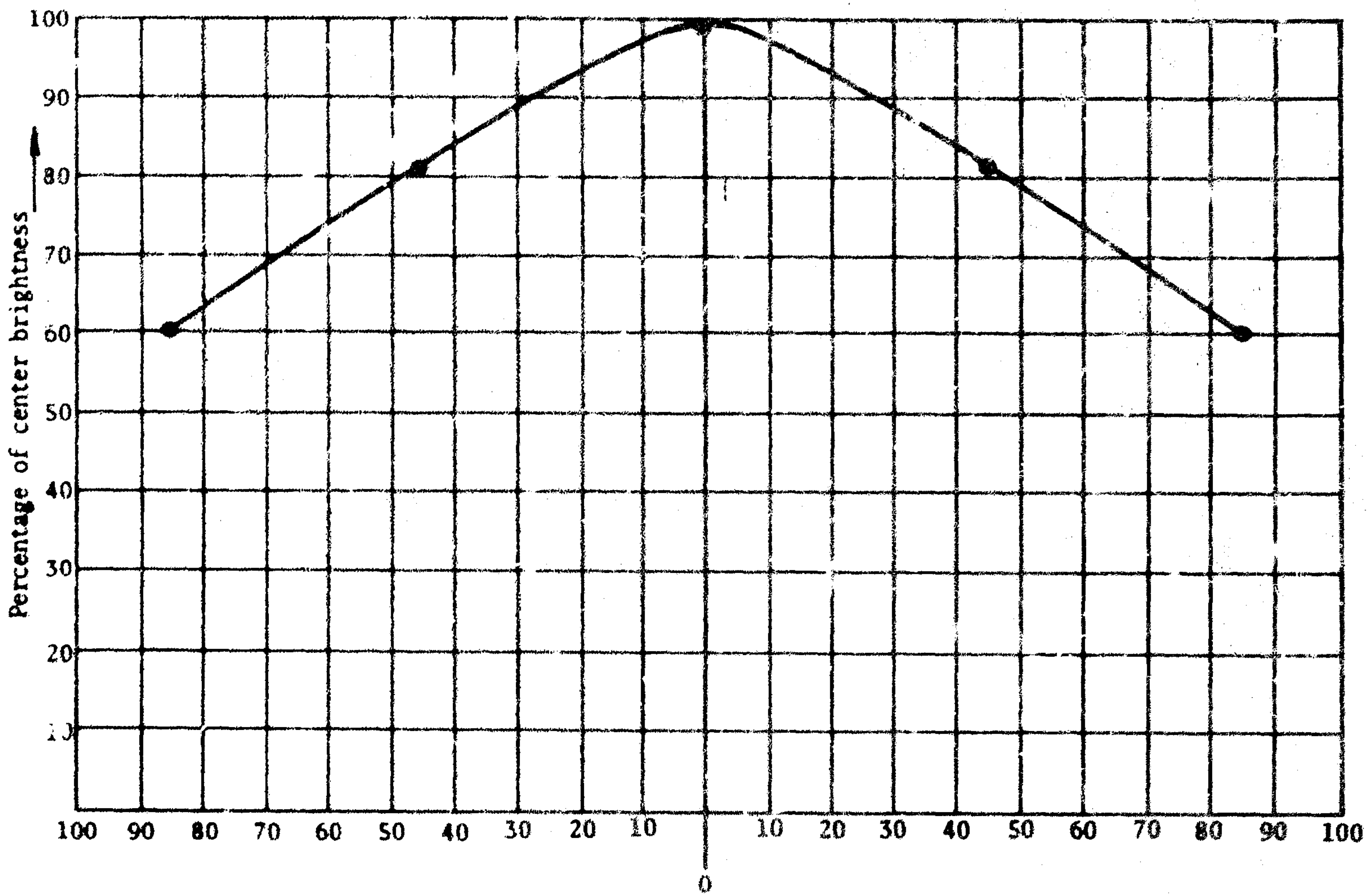


Figure 5. Decay of brightness across diameter of image intensifier

dynamically. Positioning the X-ray source at 24 to 28 inches from the image intensifier proved a good compromise and yielded a reasonably sharp shadow of the image, provided a maximum field of view, and kept spatial attenuation of intensity to a minimum.

Clear Plexiglas supported by steel braces proved suitable for the soil-container walls. Other materials tested were laminated wood and aluminum. Wood was eliminated after a few tests because of the large lateral deflections experienced at high pressures (100 psi), its nonuniform density, and its low strength. Aluminum walls, as thin as 0.25 inch, scattered and attenuated the X-ray beam quite severely, thus aluminum was eliminated. The Plexiglas offered the advantages of low X-ray absorption, transparency to light, uniform density, a relatively high modulus of deformation, and adequate strength when supported by steel braces spaced sufficiently far apart to maintain a maximum field of view.

The scattering of X rays in the soil and by the lateral walls of the container was quite high. This decreased the contrast between the soil and the lead pellets because the scattered X rays produced a foggy background on the film. Scattered X rays behave as numerous X-ray sources and cast shadows of the sand and the pellets from numerous directions onto the X-ray film. By placing a lead sheet in front of the soil sample with a window cut to the size of the field of view, the scatter was greatly reduced (Fig. 4). In essence this technique allowed X rays to pass into the soil only at the area of interest. The scatter was reduced further by using microline X-ray grids built by Liebel-Flarsheim Company of Cincinnati, Ohio. The grids are designed with fine strips of lead (60 to 150 strips per inch) to clean the scattered X rays out of the flux which has penetrated a test specimen. They are usually limited to specific focal lengths and must be chosen to match the source-to-image distance. The most successful standard size had a ratio of six to one (line thickness to width) with 60 lines per inch. The span of focal distances in the grids was 26 to 44 inches.

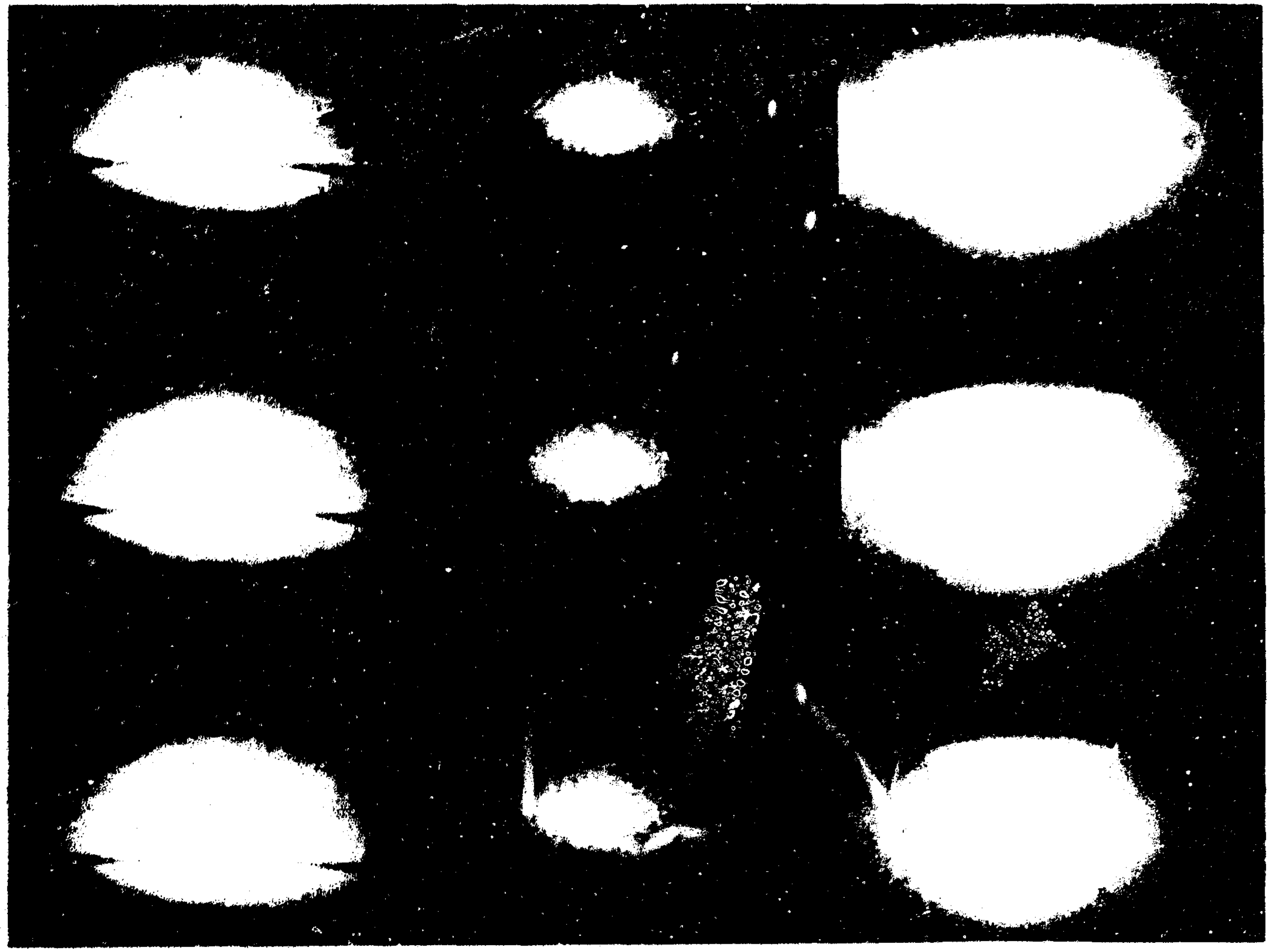
The definition of the edges of the lead pellets was very poor due to their spherical geometry. Lead cubes (0.1875 inch) were used in place of spherical pellets with much more success. Rectangular bars (0.1875 inch square, 0.50 inch long) were also used with the long dimension placed along the path of the X rays. These bars, as expected, were more easily defined than the cubes; however, lead cubes and rectangular bars are difficult to place so that the edges are parallel to the X-ray beam, and any rotation of the pellets will distort the shadowgraph and could easily be interpreted as translation.

c. Pilot Tests.

Pilot tests were performed to assess the utility of the multiple-flash X-ray system in tracking the motions of lead pellets and buried objects, and in detecting density changes in the soil. The first tests determined the quality of pictures that could be obtained through various thicknesses of soil. A 6-inch sample of dense Ottawa sand attenuated the X rays and no pictures could be obtained. Hence, a theoretical attenuation of 98 percent (Sec. III) of the maximum X-ray intensity from the Zenith Flash X-Ray System is sufficient to prevent any data acquisition with present techniques. In 6 inches of *loose* Ottawa sand sufficient X rays passed through the sample to actuate the image intensifier (Fig. 6). Although film exposure is evident, very little information is obtainable from the radiograph.

As predicted by Eq. (4) in Section V, the photographs improved rapidly as sample density and thickness were decreased since the intensity on the film was raised to the required level. Figure 6 also shows 5-mm lead cubes buried in the center of a 5-inch thick sample of medium-dense Ottawa sand and in a 4-inch thick sample of loose silt. The detail is more evident in the medium-dense Ottawa sand because of less X-ray scatter. Data-reduction techniques consisted of enlarging the frame size on an optical comparator and using x-y crosshairs to measure changes in distance between the pellets and a fixed reference frame. Considerably more detail was lost when records like these were magnified, and the technique gave results only to the nearest 30 to 50 mils. In samples of loose silt the displacements expected under high-explosive loads will be quite large, and the detection of small movements will not be as important as in dense samples. The loss of detail when Figure 6 is magnified results largely from the X-ray scatter in the soil and the resolution capabilities of the image intensifier converting X rays to visible light.

Another test was performed with 4-inch thick samples of loose soil; however, recording was limited to 1 pulse (from the multiple-flash X-ray system) directly on X-ray film in a cassette placed behind the back wall of the soil container. The inclusions were a 0.125-inch lead bar in Ottawa sand and a 0.125-inch thick lead T-section in silt. Figure 7 shows the results of this test. The image is approximately 15 percent larger than actual size due to the shadowgraph effect. From these data it is evident that resolution, detail, and field of view can all be improved by direct recording on X-ray film. For dynamic studies there are problems in film transportation and sensitivity. In this particular test the



(a) 5-in. thick, medium-dense Ottawa sand (3 frames)

(b) 6-in. thick, very loose Ottawa sand (3 frames)

(c) 4-in. thick, loose silt (3 frames)

Figure 6. Lead cubes buried in various soil samples, static tests, photographed with Zenith Model 1464 Multiple Flash X-Ray System (35-mm film enlarged)

(a) Ottawa sand (b) Silt

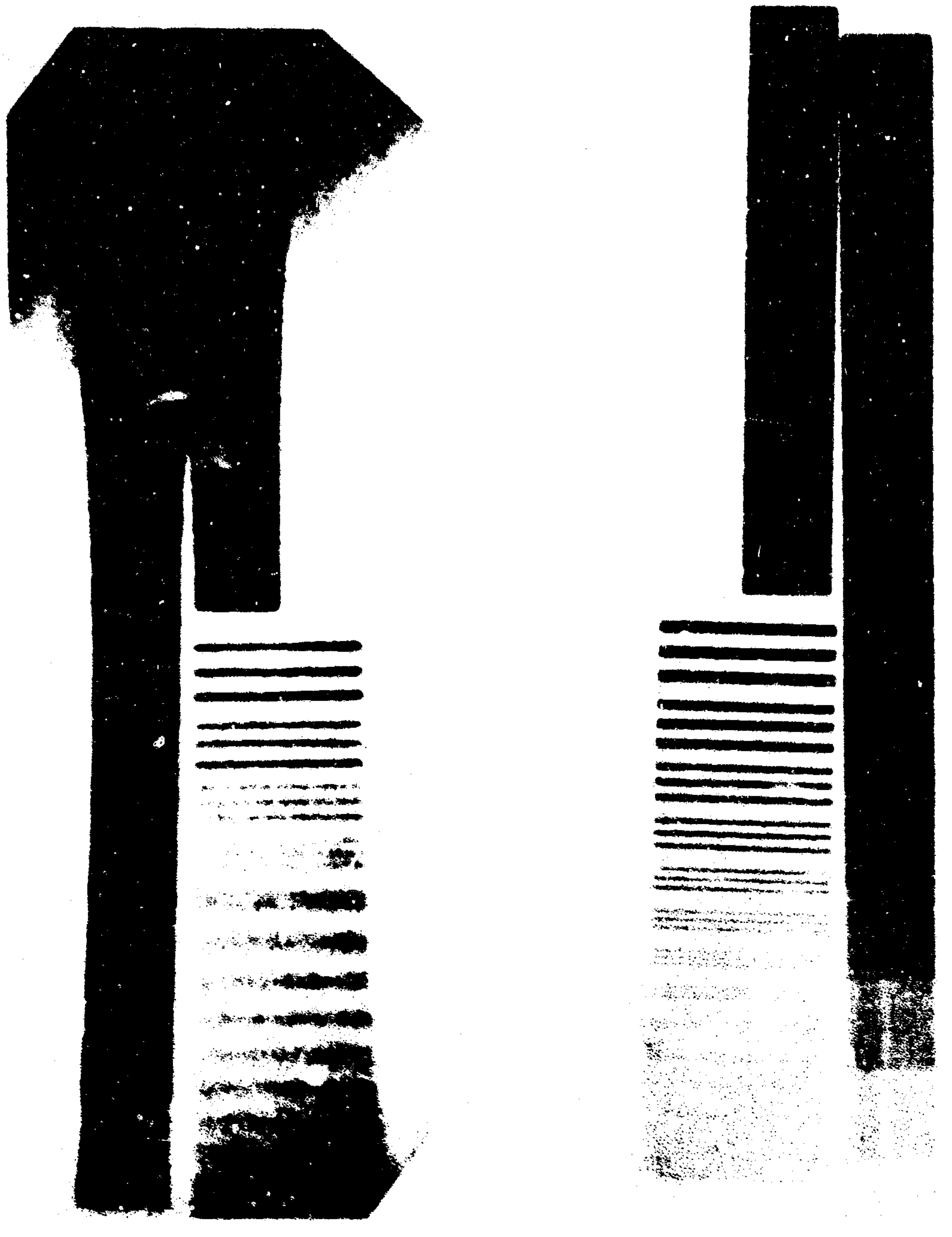
Figure 7. Direct exposure of X-ray film through 4-in. thick soil samples (Zenith Model 1464 Multiple Flash X-Ray System, scale ≈ 1 to 1)

film was pre-exposed for 1 pulse to place the film higher on the gamma curve (density versus log-exposure curve) to gain greater sensitivity. The possibilities of this technique are demonstrated in Section V where another X-ray (300-kv) machine was used with an 18-nsec pulse width; and the soil sample was a medium-dense Ottawa sand, 8 inches thick. It is evident that the detail is an improvement over the process of going through an image intensifier and photographing the converted light image with 35-mm film.

The same conclusions can be drawn from Figure 8 depicting a stepped wedge recorded on film in two different ways: (a) the picture is taken with a 35-mm high-speed motion picture camera placed behind the image intensifier; (b) the picture is taken directly by exposing a sheet of X-ray film. The line pairs become obscured after the fourth set when the picture is taken through the image intensifier. But when direct exposure is used, the line pairs are distinguishable up to the eleventh set. Density changes in the stepped-wedge section are also clearer in the direct-exposure record.

Three types of cylinders buried in soil were photographed through the multiple-flash X-ray system. The cylinders were 4, 2, and 0.625 inches in diameter and all had nearly the same wall thickness of 0.040 inch. Pellets were placed around the 0.625- and 2-inch-diameter cylinders and were loaded with a hydraulic-ram piston hitting the surface of the soil. Figure 9 shows a time history of the 0.625-inch cylinder loaded with a pulse that had a rise time of nearly 60 msec and a long dwell at the peak stress. The cylinder is in a layer of loose silt about 1.25 inches deep with medium-dense silt above and below. It is evident after close examination of the original record that some deformation occurred in the cylinder and that the soil density increased from the time of incident load, resulting in less exposure of the film. Some indication of this is seen in the difference between the first and last (twelfth) frame.

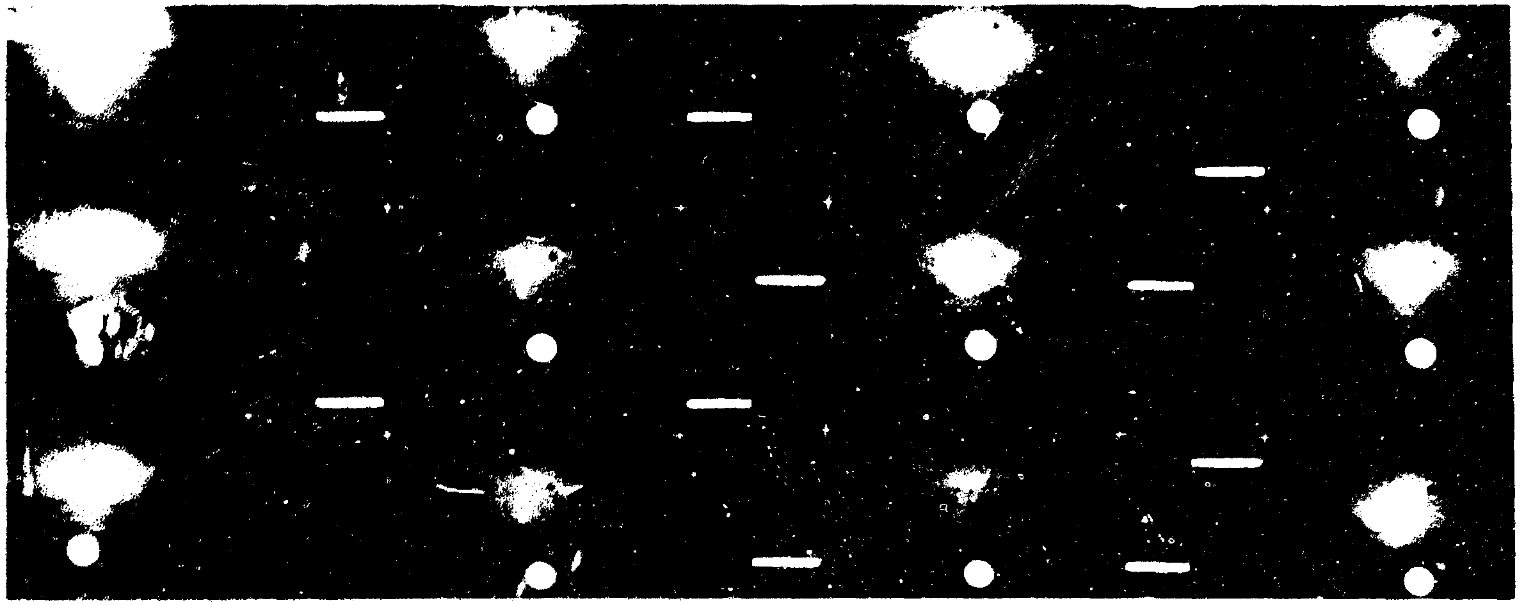
In Figure 10 the deformations are evident in the 2-inch cylinder (only a small portion of the surrounding soil is in the field of view). The 2-inch cylinder is shown with no load and with full load. From these data it is reasonable to assume that using this technique qualitative information can be collected when the deformations are large enough to change the shape of a buried object. The 4-inch cylinder was loaded to failure and is shown in Figure 11 just about 3 minutes before the load application and just after collapse.



(a) Photograph after image intensifier with 35-mm shellburst Linagraph film

(b) Direct exposure on X-ray film

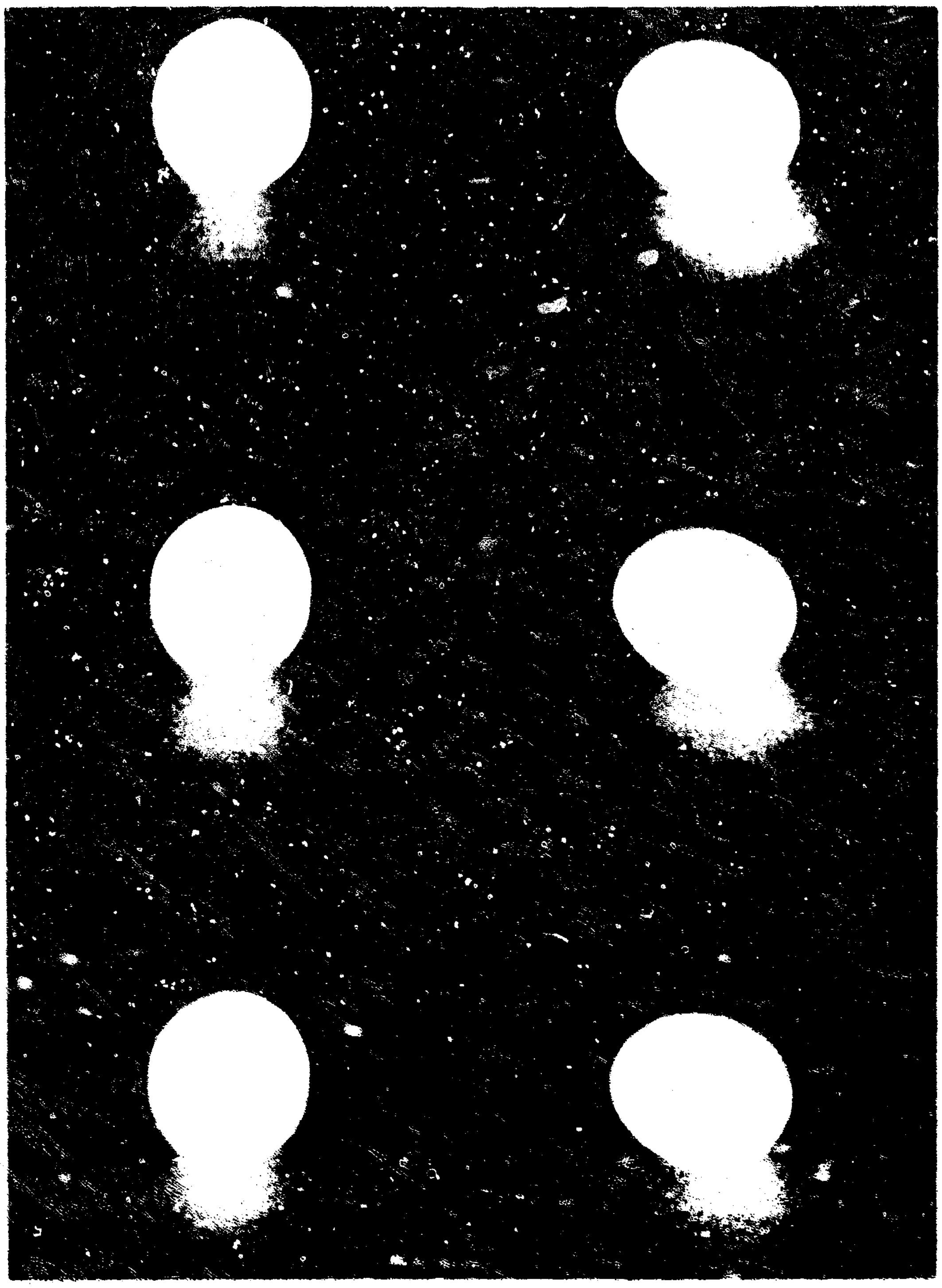
Figure 8. Stepped-wedge photographs with multiple-flash X rays



No load, more exposure on film

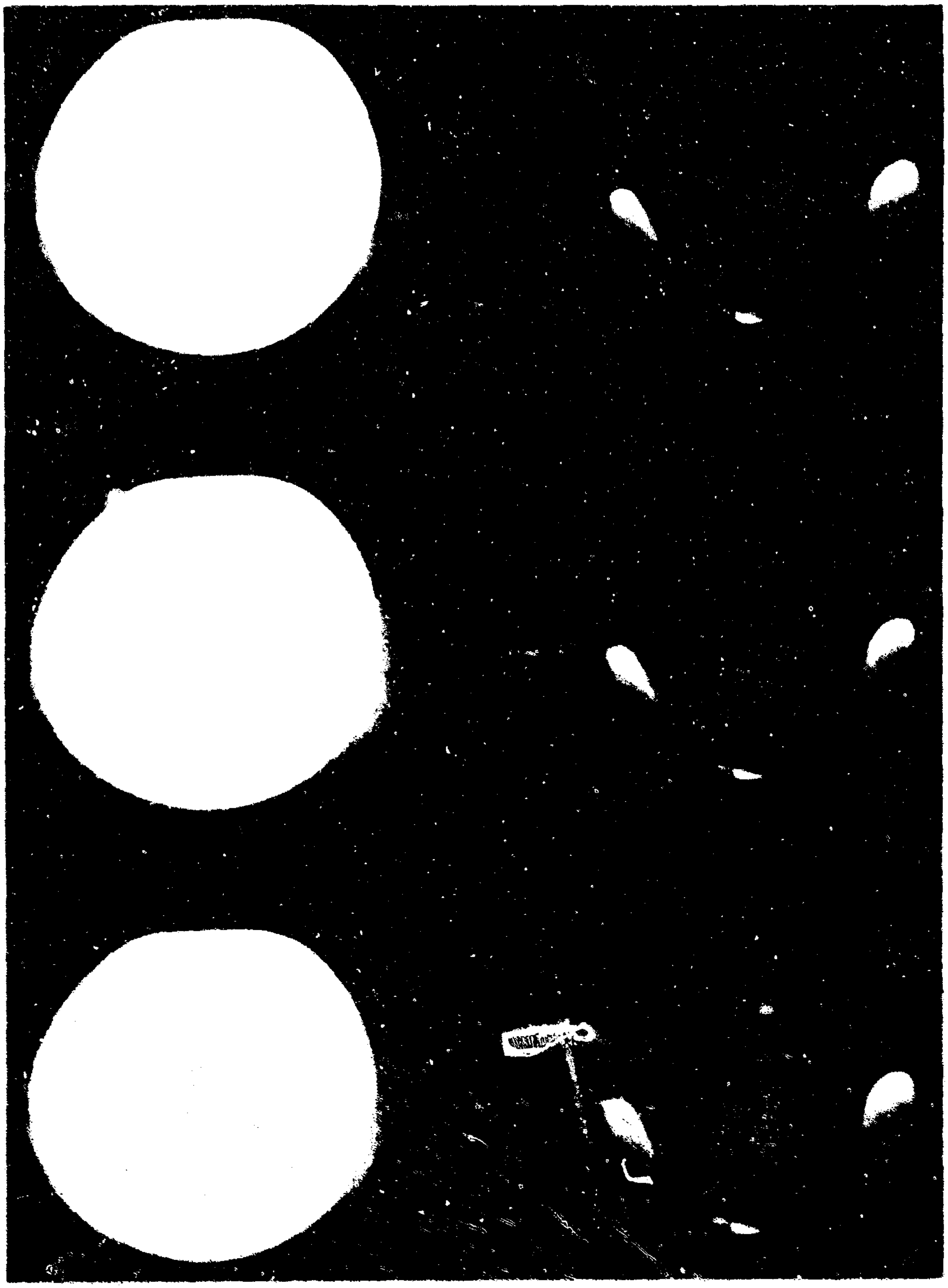
Peak load 100 psi, less exposure on film

Figure 9. X-ray record of 0.625-in.-diameter cylinder buried in Ottawa sand and loaded dynamically (direct 35-mm film)



No load — Peak load 100 psi

Figure 10. X-ray record of 2-in. diameter cylinder buried in Ottawa sand and loaded dynamically



No load Failure

Figure 11. X-ray record of 4-in. diameter cylinder buried in Ottawa sand and loaded to failure

3. <u>Field Emission Corporation Cineradiographs</u>.

The Field Emission Corporation has applied a technique for the generation of X rays which results in a number of desirable features. The most significant are (a) a very high repetition rate (10^6 pps, sometimes the frame rate per second, fr/sec, is given) for a multiple X-ray source system; (b) 10^5 pps with a single X-ray tube and multiple pulsers; and (c) a means of increasing the time interval between pulses (from 1-μsec and 10-μsec minimum for the multiple and single X-ray source systems, respectively, to much longer time intervals). This allows adjusting the pulse-repetition rate to fit a pulse pressure-time record as shown in Figure 12.

A schematic is shown in Figure 13 of an existing Field Emission Corporation high-speed cineradiographic system (Fexitron Model 735-3-C-235) with a single-tube output. Fexitron is a trade name for the field-emission X-ray device. The pulse and the tube numbers apply to a 150-kv system; however, the appropriate pulser and X-ray tube are required to withstand much higher potentials. The equipment employs a passive-energy storage unit for each pulse or frame (i.e., a pulser). Associated with each storage unit is a delayed-trigger amplifier and an isolating diode. All pulsers are therefore connected to the X-ray tube by their isolating diode (Model 546 Diode Rectifier).

The system is operated by charging all pulsers with the Model 314 High-Voltage D.C. Power Supply. The time delay from time zero (t_0) at which each pulser is sequenced to fire is set into its associated delay generator. With a firing trigger at t_0, all delays are initiated and the X-ray tube fires as each delay elapses. With the single X-ray tube system any number of pulses, along with any pulse-to-pulse time interval in excess of 10 μsec, becomes possible when more pulsers and associated isolation diodes, as well as triggering units, are added.

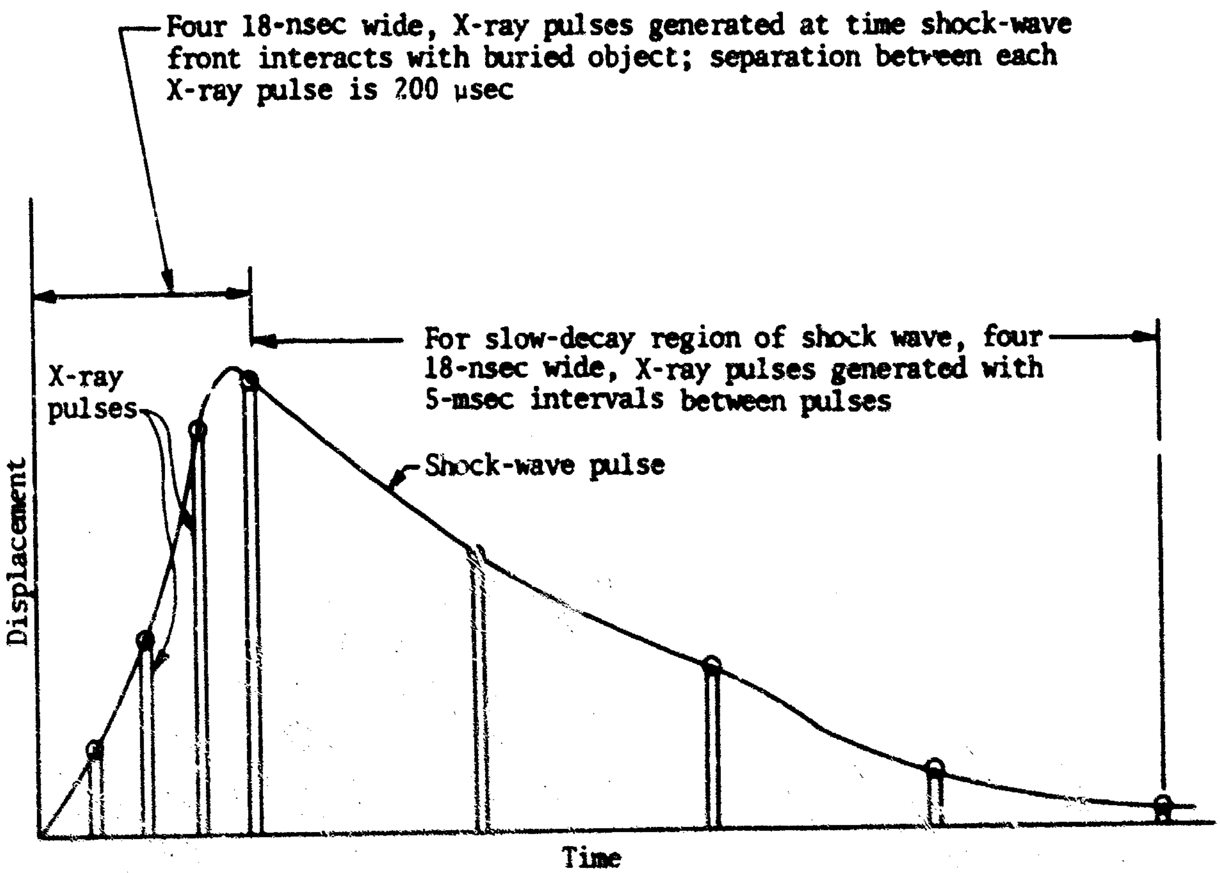


Figure 12. Application of X-ray system with variable, pulse-repetition frequency

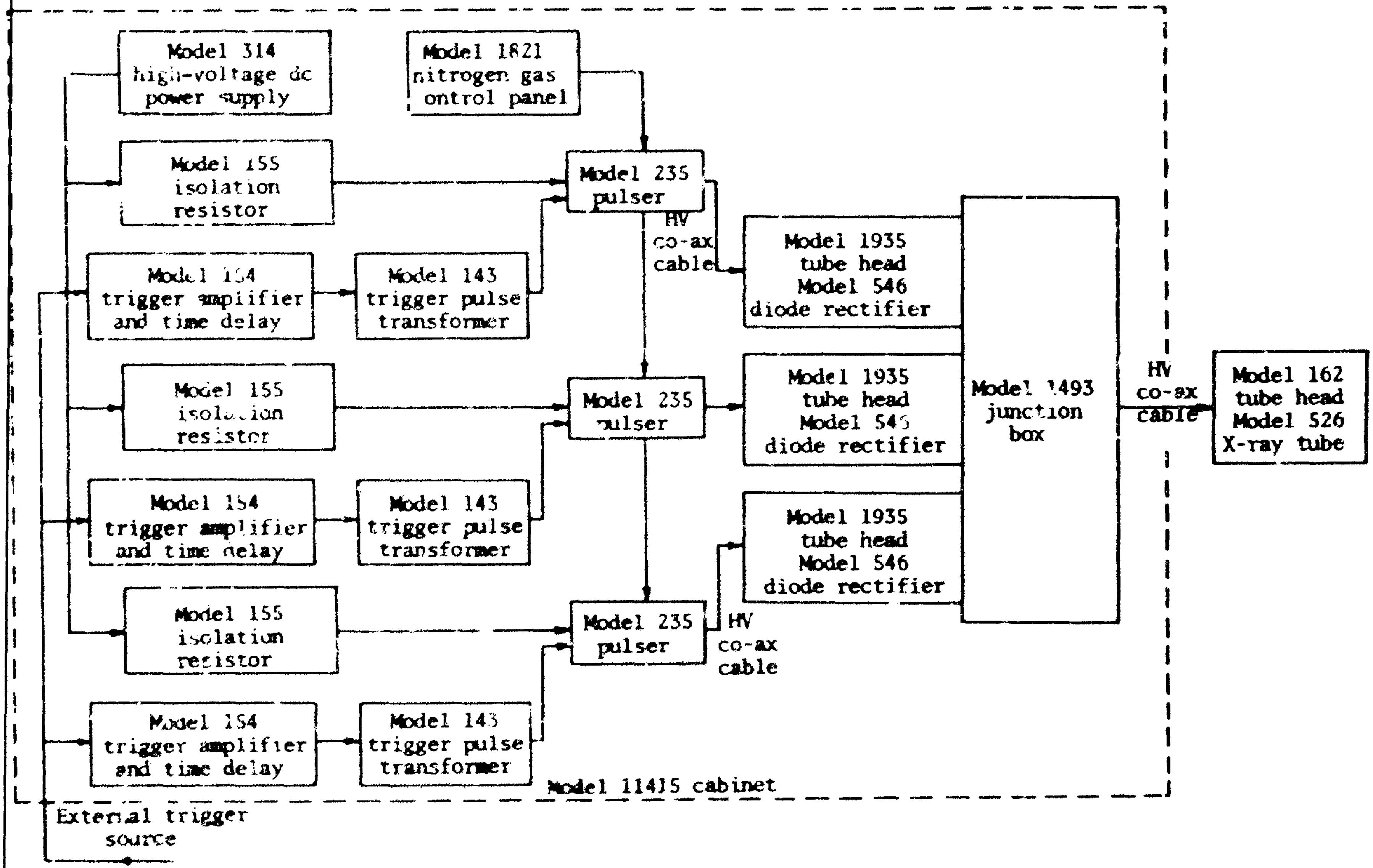


Figure 13. Schematic of Field Emission Corporation Single-Tube Cineradiograph Fexitron Model 735-3-C-235

The specifications for the Field Emission Corporation High-Speed Cine-radiographs are as follows (the general model numbers describe specific systems):

```
     Basic system no.
     /           No. of channels
    /           /           Cabinet-mounted pulsers
   /           /           /          Pulser model no.
  /           /           /          /         No. of X-ray tubes
 /           /           /          /          /
735 --------- n --------- C ------- 235 -------- m
```

Pulser Model Nos.:	235	233	265
X-ray tube accelerating voltage, kv	150	300	600
Output current, a.	2,000	1,400	1,500
Output impedance, ohms	75	215	400
Pulse width, μsec	0.07	0.01	0.1

X-Ray Tube Model Nos.:	529	515	537
Peak power, megawatts	300	420	900
Joules per pulse	21	42	90
Source size, diameter in mm	3.0	4.0	4.0
Dose rate at tube surface, roentgens/sec	1×10^8	1×10^8	6×10^8
Penetration, inches of aluminum	(at 1 ft) 2.8	(at 1 ft) 6.0	(at 2.5 ft) 7.0

X-ray pulse shape..............square

X-ray pulse-repetition frequency....................10^6 pps (multiple tube), 10^5 pps (single tube)

Pulse intervals............ ...each interval variable from 1 μsec (multiple tube), 10 μsec (single tube), to 100 msec

Cone of radiation..............approximately 30° cone

Power requirements.............120 volts, 60 cps, 75 watts continuous power for each trigger amplifier; 250-watt intermittent power for Model 314, 30-kv dc, 5-ma power supply

The advantages and disadvantages, based on a single-tube Fexitron 300-kv system with an 18-nsec pulse width (Model 730-6-C-271 with a Model 515S X-ray tube) which was very recently released by Field Emission Corporation, are as follows:

a. Advantages.

(1) The Field Emission system is simple, easy to operate, and reliable.

(2) The Field Emission model has very high stop-motion capability on transient events. (For example, a radiograph of a shock-wave front having a velocity of 3,000 fps is smeared out 0.65 mil by the 18-nsec pulse and 1.08 mils by the 30-nsec pulse.) A soil set into motion with a velocity of 100 fps by the shock wave has that motion smeared 0.02 mil by the 18-nsec pulse and 0.036 mil by the 30-nsec pulse.

(3) The Field Emission single-tube X-ray model can generate X-ray pulses 18-nsec wide with any pulse separation from 10 μsec to 100 msec.

(4) The Field Emission model is able to increase the number of pulses in a pulse sequence by adding pulser units. (The feasibility of a single-tube X-ray system generating six X-ray pulses with the controllable repetition rate has been demonstrated.)

(5) A Field Emission multi-channel system incorporating more than one X-ray tube and pulse is available. For example, a four-tube X-ray system can provide 4 pulses with a megacycle-frame rate. This requires arranging the X-ray tubes around the object to be radiographed or along the path of stress wave propagation. The 300-kv system has adequate output to allow recording the soil movement (Fig. 14) directly onto Kodak Royal Blue film. (This simplifies the entire system considerably since the image intensifier and lens-coupling systems are not required.) In addition, for the tests to be conducted, the application of a higher voltage 600-kv system to soil experiments could remove the system from a marginal region of operation.

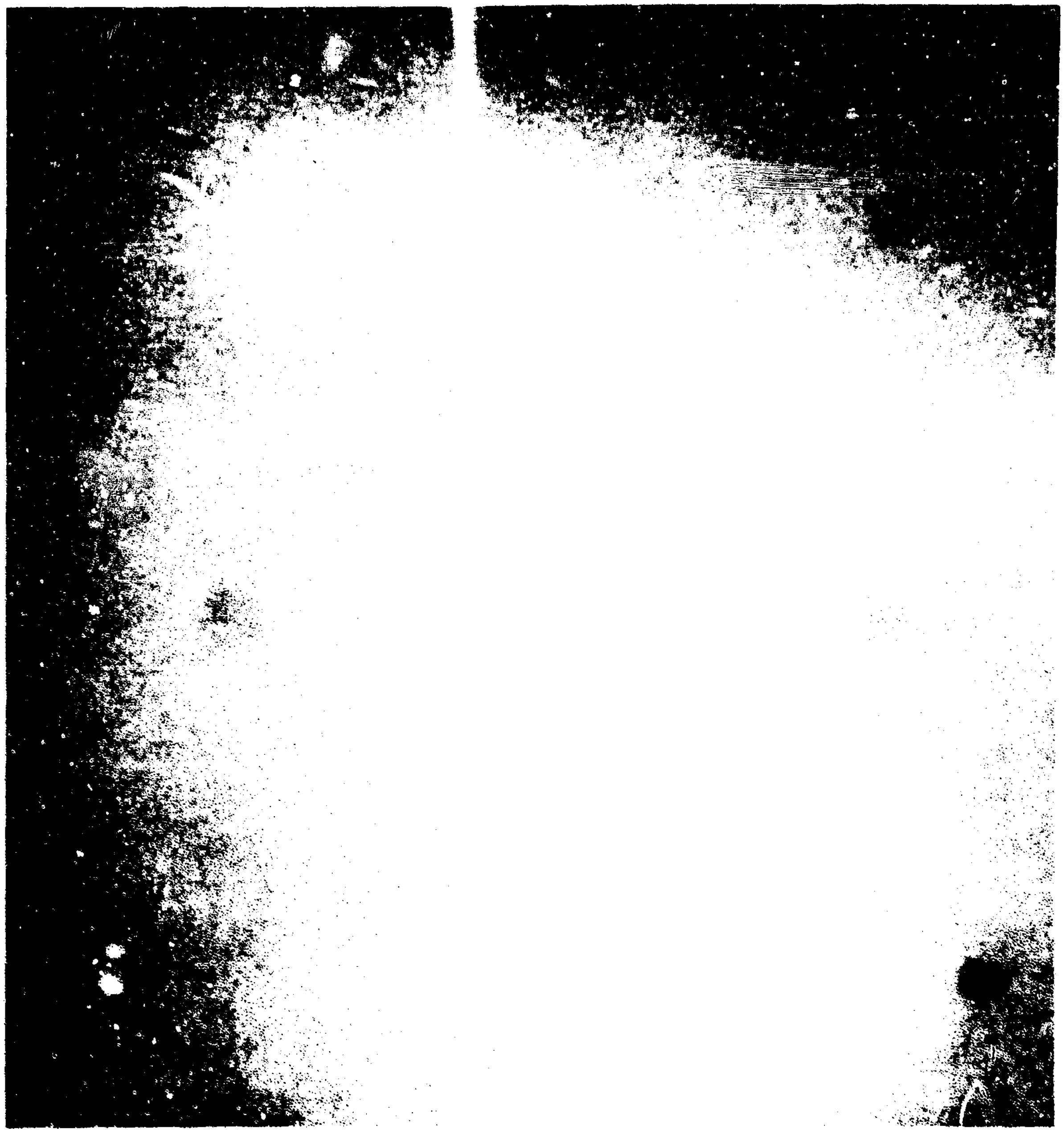
(6) Field Emission has complete and reliable pulse synchronization.

(7) Field Emission has a guaranteed X-ray-tube life of 150 pulses; however, the tubes have performed satisfactorily for as many as 600 pulses. Approximate cost of one X-ray tube is $680 or $4.53 per guaranteed pulse.

(8) The Field Emission System requires no cooling.

(9) The Field Emission System offers better resolution if the film is placed directly behind the soil bin. The resolution is limited only by tube spot size, source-object and object-film distance, and scattering by the soil.

(10) The Field Emission System has low-input power requirements.



20% moisture added　　　　Rubber membrane　　　　Dry sand

Figure 14. Direct-exposure X-ray record of six 0.1875-in. lead cubes buried in 8 in. of medium-dense Ottawa sand at various locations along the thickness (1 pulse, 300-kv Field Emission Model 735-3-C-235)

(11) The Field Emission X-ray tube can be operated remotely up to 60 feet from the pulser and control panels by use of a coaxial transmission line. (This can be a decided advantage in soil experiments.)

b. Disadvantages.

(1) Without an image-intensifier tube, the Field Emission Corporation System will require special equipment to move rapidly large sheets of film (possibly on a drum) past the object during the X-ray-pulse exposures which are synchronized with the shock-wave transit through the soil bin. This is particularly true if a large field of view is required.

(2) The Field Emission X-ray tube life is short; however, this is offset by the low cost of the system compared to other systems.

(3) The spot-size diameter is 4 mm for the 300- and 600-kv systems as compared to 1 mm for the 105-kv system, thus causing increased shadow unsharpness.

(4) The pulse-forming network is a Marx surge generator in which the voltage has been shown to vary from pulse to pulse on other systems and thus produce a generation of X rays having different, principal wavelengths. However, it has been stated by the manufacturer that the X-ray fluctuation from pulse to pulse is under 2.5 percent for the Field Emission System and thus poses no problem. In addition, the X-ray-tube voltage and impedance match between the load (X-ray tube) and the coaxial transmission can be easily monitored by observing the voltage waveform across a small-series resistor.

It is important to note that there are possibly other disadvantages in the Field Emission Corporation System as far as soil testing is concerned, but these can only be determined by laboratory tests. Since this system was not available for evaluation at CERF, the bases for analysis are the manufacturer's specifications and the history of its performance.

4. Experimental Results with Field Emission Corporation X-Ray System.

Field Emission Corporation has very recently completed and tested the Model 251 Pulser which is used in conjunction with the 300-kv X-ray system. To demonstrate the penetration capability of this X-ray system for application to soil studies at CERF, a number of tests were conducted at the Field Emission Laboratories at McMinnville, Oregon, using Ottawa sand and 0.1875-inch lead cubes.

In one of the tests a 300-kv, model 5155, X-ray tube was placed 2 feet from Kodak Royal Blue film (with industrial screens which utilize calcium tungstate), and an 8-inch thick soil bin half filled with dry Ottawa sand and half with wet Ottawa sand (20-percent water by weight) was placed directly in front of the film. In the sand in each half of the bin three lead cubes were positioned: one about an inch from the front of the bin, one in the middle of the bin, and one about an inch in front of the film.

Figure 14 shows the results. The edge sharpness is excellent for the cubes nearest the film since very little X-ray spot-size or scattering distortion is possible. This is contrasted with the detail associated with the cubes nearest the X-ray source.

The ability of the X-ray system to "look through" 8 inches of Ottawa sand and still have enough energy to expose the film directly without image intensification is of major importance. Close scrutiny of the original film shows a definite difference in exposure due to the slight difference in densities between the dry and wet sand.

The tests were completed in June 1965. The film clearly demonstrates that the 300-kv system is capable of providing the required X-ray intensity and resolution for a large number of the soil experiments planned at CERF.

SECTION V

DESIRED FLASH X-RAY CHARACTERISTICS, ALTERNATE APPROACHES

1. Desired System Characteristics.

Before alternative approaches are presented utilizing some combination of X-ray tube and associated equipment, it is necessary to identify and discuss some of the requirements in a pulse X-ray system for soil experiments.

A number of controllable areas in a pulsed radiographic system which can be altered to produce desired results are depicted in Figure 4. In CERF research, radiographs of dynamic tests in soil are required. A high-speed stop-motion radiographic system (cineradiograph) capable of obtaining pictures of shock-wave-induced motions of objects embedded in soils is required. The usefulness of the photographically recorded event is based on the following:

a. Stop-Motion Capability.

There are two methods of stopping the motion of the event: (a) by having a very narrow X-ray pulse, less than 100 nsec; or (b) by having a continuous X-ray source and controlling the film-exposure time by some means of shuttering (electronic or mechanical). The amount of smearing is a function of how much certain objects within the field of view have moved during the pulse-time or exposure interval. For all practical shock-tube research an 18-nsec pulse causes no discernible smearing or overlap of the radiograph even for air shock.

b. High-Resolution Capability.

To clarify high-resolution capability in radiographs for soil research, it is necessary to treat the resolution of the components of the X-ray system, the soil medium, and the test model. (This usually includes the structure and the soil in which it is embedded.)

Consider the zones which can be controlled (designated as zones 1-8, Fig. 4). Starting with zones 1, 2, and 4--and, at first, assuming the intervening medium to be air--the resolution is controlled by the X-ray target size, the object distance, and the image plane (either a photographic plane or the calcium tungstate screen of the image intensifier). Figure 15 shows the extent of these resolution zones. Here, the geometry of the Field Emission Corporation and the Zenith Multiple Flash X-Ray systems is shown: (a) with the photographic film a distance behind the test object (s_1), and (b) with the image-intensifier screen a distance behind the test object (s_2).

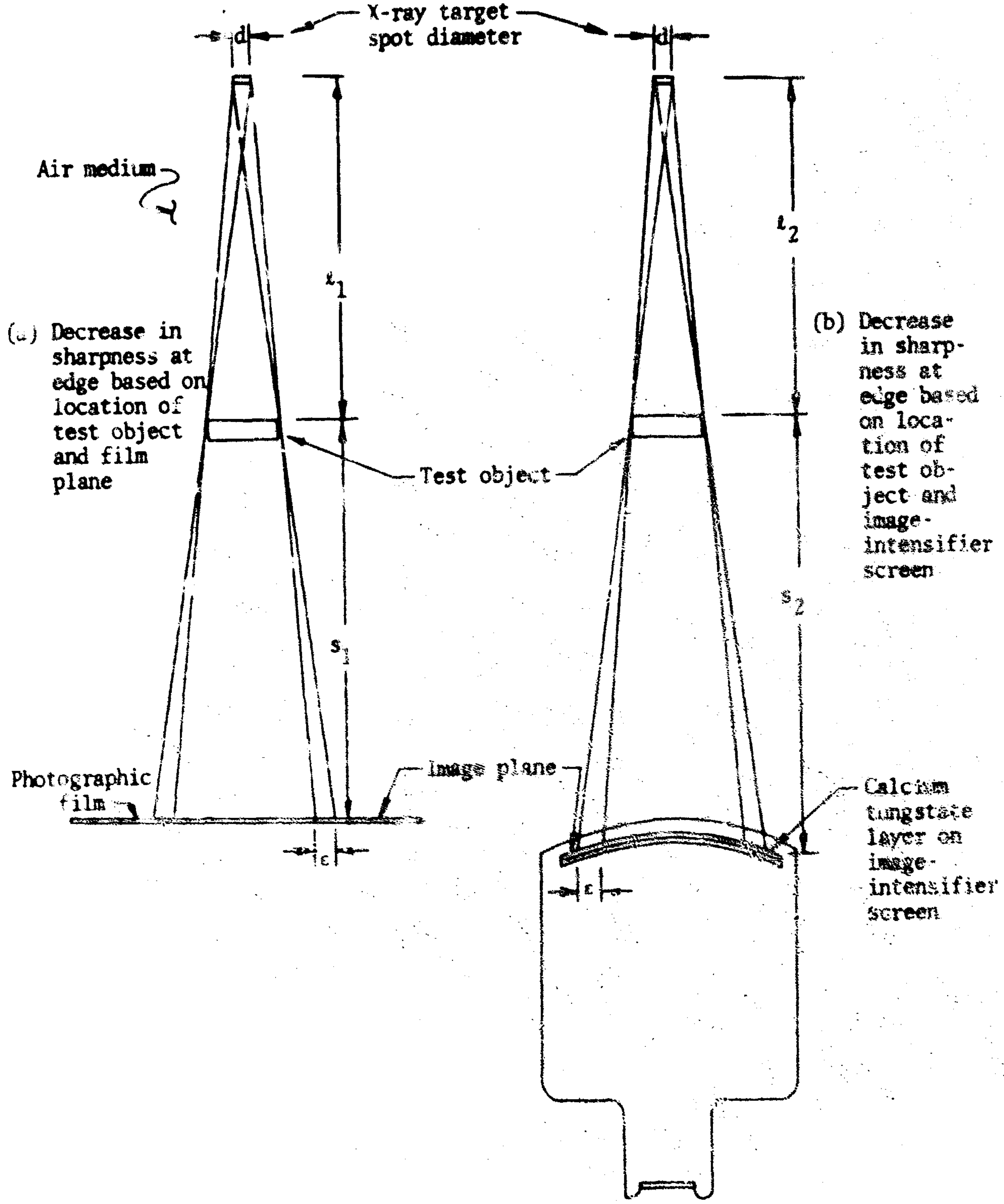


Figure 15. Detail of edge of test object based on X-ray target spot size and system geometry

In dealing with the geometrical arrangements shown in Figure 15, one encounters two effects which decrease the shadow edge sharpness. These are the penumbra (partly lighted shadows) and diffraction effects; see Figure 16 in which b is the distance to the first maximum. The penumbra degradation, unit of length (ϵ), is given in the image plane by the following expression:

$$\epsilon = d \frac{s}{\ell} \tag{4}$$

where s/ℓ is defined as a magnification (or reduction) factor. This equation clearly shows that the ways to make ϵ small are (a) by making the X-ray-tube spot size as small as possible, largely by proper focusing of the electron beam; (b) by placing the test object next to the film, or as close to the image-intensifier screen as possible; and (c) by removing the X-ray source to infinity.

The radiographic technique of placing the test object next to the film is called *microradiography*. This method provides resolution capabilities for thin objects in the range of 1,000 ℓp/mm. The resolution is primarily limited by the grain size of the film. Clearly, one cannot take advantage of this resolution for soil experiments because the test object cannot be placed in contact with the film, and it is usually relatively long when compared to the length of the soil being penetrated in the soil bin. Nor is there any object magnification with this technique unless the dimension ℓ (distance from X-ray spot to test object) is less than s_1 or s_2 (distance of photographic film or image-intensifier screen behind test object, respectively). If the test object could be placed in contact with the film, there would be no diffraction effects to worry about.

By removing the test object from the film surface, one gets into the realm of shadow-projection microscopy. Not only are penumbra effects encountered but diffraction effects as well. By making the distance ℓ large, the penumbra is reduced as is the X-ray intensity. A trade off becomes necessary. In making measurements in soils, the research engineer is forced to use shadow-projection radiography since the test object cannot be placed next to the film; the object must be well within the soil bin to escape the side-wall effects; consequently, some penumbra and diffraction occur. The penumbra can be kept low because of the reduction factor (s/ℓ).

Probably the most degrading region for resolution is given by zone 3 in Figure 4. This zone is the test bin which can be filled with Ottawa sand or

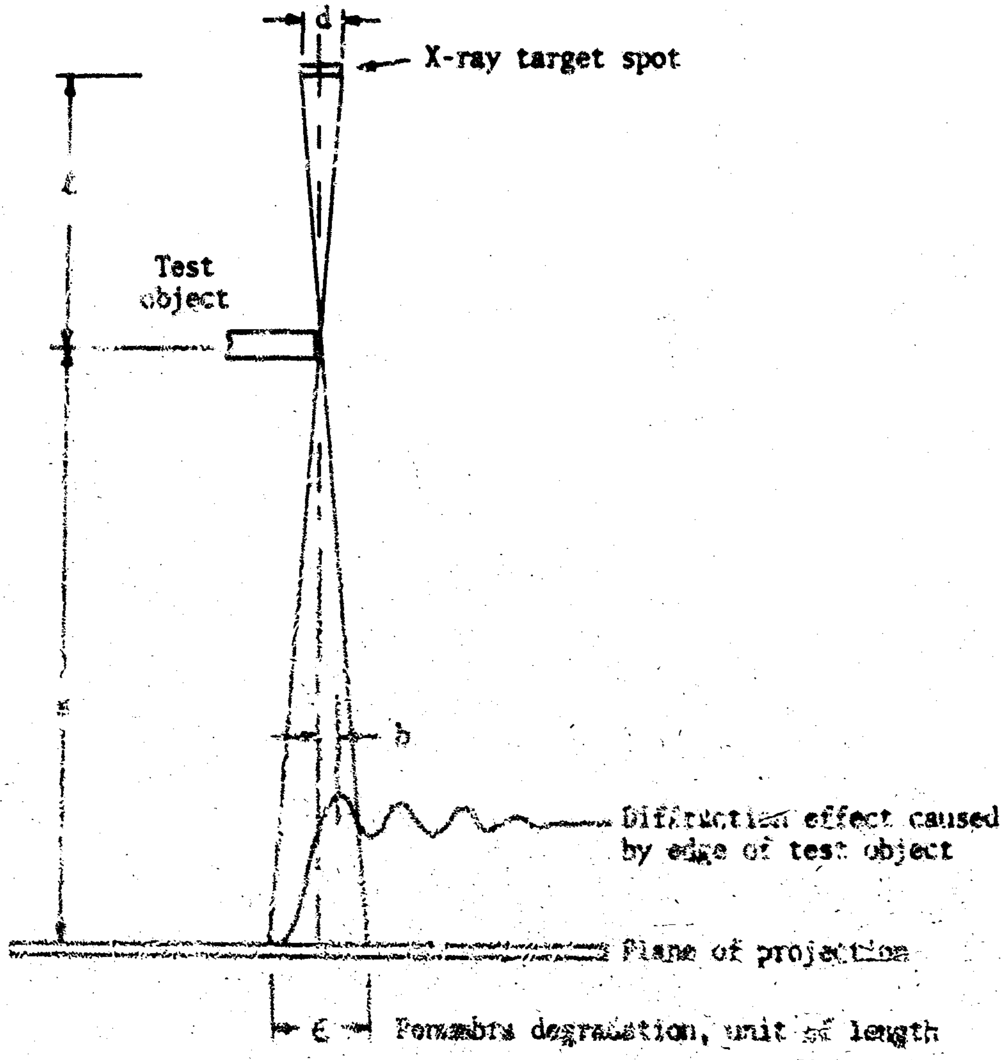


Figure 16. Decrease in sharpness at edge by diffraction and penumbra

clay. The sand causes scattering of the X rays into the shadow of the object which can badly reduce the resolution.

Not only does the sand scatter the radiation but also the soil container, the object radiographed, the film holders, and any object or material in the path of the primary radiation beam. The effect of scatter is to reduce the contrast, detail, and clarity of the radiographed object. Lead foil, in intimate contact with the film, absorbs the white and scattered radiation more than it absorbs the primary radiation, thus reducing the bad effects of scattered radiation. Venetian-blind-type filters or lead screen meshes placed at the back of the soil bin can greatly improve the resolution by attenuating the scattering which falls into the test-object shadow. A lead mask which acts as an aperture, limiting the volume of matter exposed to the primary radiation, is also effective in reducing scattered radiation and should be used.

A resolution figure of merit, probably ℓp/mm, is required for different soil media and filter combinations. The resolution of the input screen on the image intensifier is usually about 2 ℓp/mm maximum. This is two or more orders of magnitude less than the resolution possible by the microradiograph technique. The image intensifier has, however, two very important advantages: (a) the capability of raising the intensity of the light level by a factor of more than 2,000, and (b) the utilization of the weaker, high-contrasting X rays (longer wavelengths) generated by lower voltage systems.

Thinning out the calcium tungstate surface on the input of the image intensifier would reduce the scattering in this transfer medium and thus improve the resolution considerably. This operation, however, becomes a major development in itself. (It can be done, however, with industrial film in the cassette directly behind the soil bin.)

There is a further slight degradation in the resolution throughout zones 6, 7, and 8, and in the fluorescent screen, the coupling-lens system, and the camera, resulting in an overall output resolution of about 1.5 ℓp/mm.

c. Contrast, Latitude, and Sensitivity.

To make the photographed film useful in the analysis of object motion in soils, every technique must be used to ensure distinction between small differences in the blackening of the film. The information is sometimes described in terms of the number of shades of gray on the film. Experiment has indicated that the optimum contrast is $s = 0.7$ to 0.9 where $s = \log_{10} I_o/I_t$.

The human eye can detect with certainty a minimum difference in grays between adjacent areas of s = 0.02 (or approximately 5-percent difference in intensities).

Aside from the photographed shadows, contrast is the difference in density in a radiograph produced by a change in the thickness of the object or its material content. For simple test objects, as shown in Figure 4, the length of the object is maximum to ensure a high value of s. However, where variations in thickness or density which need to be ascertained are small, it is necessary to resort to the longer wavelength X rays, the selection of materials whose absorption-edge wavelength can be matched by the source X ray, and high-contrast films. Where it may prove advantageous to resort to long wavelength X rays, the use of an X-ray tube of a different anode should be considered. It is important to note, however, that the wavelengths of characteristic X rays do not vary continuously.

Both the Zenith Multiple Flash X-Ray and the Field Emission Corporation X-Ray systems have limited control over the accelerating potential and thus the generation of longer wavelength radiation. Their lowest operating voltage levels still place the principal X rays in the hard X-ray spectrum. Various films and techniques have been developed to provide high contrast. For example, where the range of radiographed intensities is too wide to be recorded by a single high-contrast film, the cassette can be loaded with two high-contrast films of different speeds. The exposure is set so that the thick portions of the test object are satisfactorily recorded on the faster film, and the thin portions on the slower film. For detail, the film can be viewed separately or superimposed.

Latitude is the extent of object thickness that can be reproduced in the range of densities encountered. If density variations in a soil medium do not meet the s value of 0.02, then there is little hope of getting readable photographs. One of the tests planned for evaluation of a stress gage concerns observation of gage-case motions. The latitude, however, may be inadequate to evaluate certain dynamic characteristics of the gage due to shock-wave loading.

Sensitivity is a combination of contrast and latitude.

d. Gain Capability.

The intensity-gain characteristic of an image intensifier provides certain advantages in a pulsed X-ray system. These advantages are being able (a) to raise the intensity of the visible image (transformed from the X ray to a visible region) to a point where the film exposure can be set mainly by the camera controls; (b) to use such low X-ray intensities that the hazards of

X rays to personnel are greatly reduced; and (c) to use the longer wavelength X rays for improved contrast.

e. Motion Picture.

Through the application of an image intensifier, the X-ray shadowgraph is transferred to a visible image. This application allows reducing the image by optical methods so that the film can be exposed in a high-speed (16- or 35-mm) camera. The camera can film the pulse-by-pulse data from the X-ray unit; thus no framing or film transport problems are encountered.

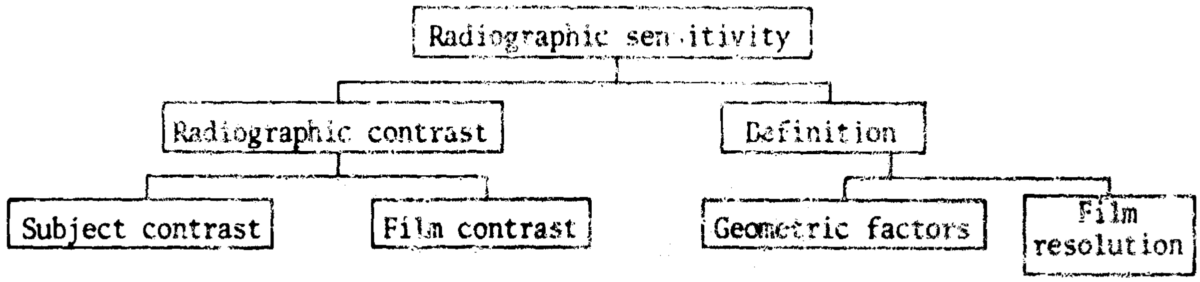
In using microradiography or shadowgraph microscopy with a pulsed X-ray system having a sequence of 8 or more pulses with a time separation of 1 msec between pulses, the problems become severe when one tries to get 8 frames by moving a large strip of film (possibly 1 x 12 feet) in the plane of zone 3 in Figure 4. By limiting the area of interest to the shadowgraph of a single test object in the soil bin, which can usually be contained in an area about 4 x 4 inches, a continuous film transport can be made in which the film size can be reduced considerably. However, if a shadowgraph of the entire soil bin is required, one is again faced with the problem of moving large sheets of film rapidly past the object or using an image intensifier in combination with a 16- or 35-mm camera.

Most of the comments on subject contrast, film contrast, geometric factors, and film-resolution factors are briefly summarized in Figure 17 in conjunction with radiographic sensitivity (Ref. 10). Figure 17 shows the various factors which influence radiographic sensitivity. A high-radiographic sensitivity would mean that one could inspect a radiograph and detect small inhomogeneities or density variations.

2. Development.

Some rather significant advances have been made in image intensifiers which could be incorporated into X-ray systems and might possibly provide higher contrast and resolution of test objects in soil. There are a number of ways in which these improved image intensifiers could be applied.

Consider the application of the tandem arrangement of two image intensifiers in conjunction with the Zenith Multiple Flash X-Ray System as depicted by Figure 18. Although the following concepts have not been thoroughly analyzed, they are offered to show the potential improvements possible through use of these intensifiers.



Subject contrast	Film contrast	Geometric factors	Film resolution
Affected by:	Affected by:	Affected by:	Affected by:
a. Thickness differences in specimens	a. Type of film	a. Source of spot size	a. Type of film
b. Radiation quality	b. Development time, temperature and agitation	b. Source-film distance*	b. Type of screen*
c. Scattered radiation caused by object and soil medium in which it is placed	c. Density	c. Specimen-film distance*	c. Radiation quality*
	d. Activity of developer	d. Abruptness of thickness changes in specimens	d. Development
		e. Screen-film contact	

Reduced by:

a. Masks and diaphragms

b. Filters

c. Lead [illegible]

*These factors are controlled indirectly by use of an image intensifier.

Figure 17. Factors affecting sensitivity

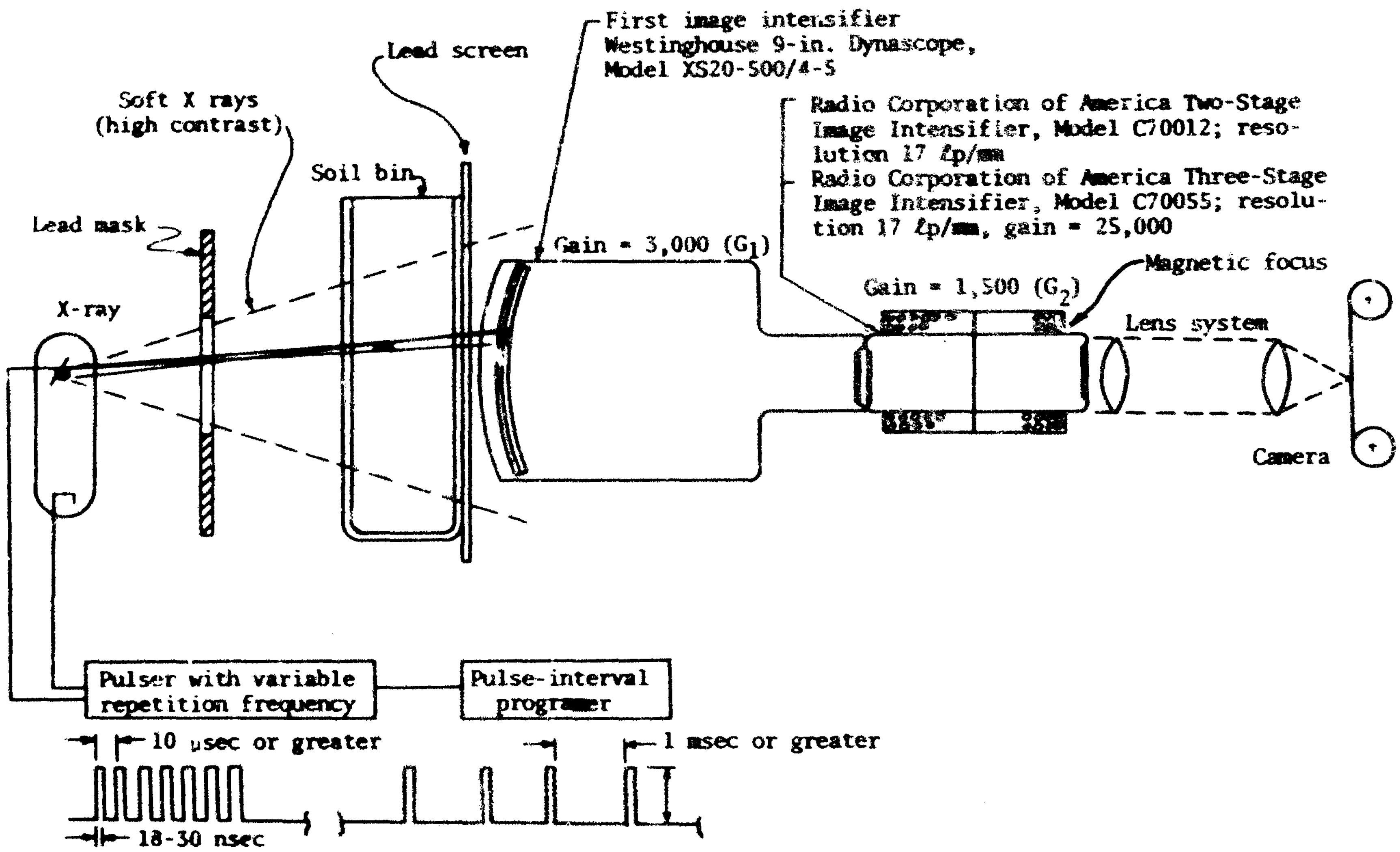


Figure 18. Pulsed X-ray system with high-gain image intensifiers in tandem

The gain of the tandem arrangement of two-image intensifiers ranges from approximately 4.5×10^6 to 7.5×10^7 (65-79 decibels). The resolution for the Westinghouse 9-inch Dynascope, Model XS20-500/4-5 Image Intensifier is approximately 2 ℓp/mm. For the Radio Corporation of America units, resolution values are 10-17 ℓp/mm. With such high, light-intensity gain, the X-ray intensity at the input screen of the first image intensifier can be greatly reduced. For example, the accelerating potential of the Zenith X-ray tube with certain modifications might be reduced to considerably less than its 50-kv, minimum-operating level. If such a reduction in voltage could be made by modifying the Zenith Multiple Flash X-Ray System, the following improvements would result:

(1) Softer X rays could be generated so as to provide greater contrast between the soils and the test object, provided the X rays could penetrate the media.

(2) Since a reduced accelerating potential can be more easily controlled, it should be feasible to increase the pulse-repetition frequency and make it variable. Repetition frequencies as high as 40 kilocycles (kc) should be possible (sampling at 40 kc allows one to resolve 20-kc information). Also, the pulsed energy impinging on the tungsten target of the X-ray tube is reduced considerably, thereby allowing the X-ray tube to be operated continuously if desired. The lowered potential should also largely eliminate the problems with kickback surges experienced with the 150-kv pulses which invariably trip the safety relays in the Zenith Multiple Flash X-Ray System.

Finally, there should be some additional light intensity resulting from the very high gain of the second image-intensifier stage which could be traded off in the reduction of scattering by the addition of lead screens on the back side of the soil bin. The reduced X-ray levels are, of course, safer to work with.

Other combinations worth considering, which may or may not utilize the image intensifiers, include the following:

(1) Modified Zenith Multiple Flash X-Ray System with image intensifiers in tandem, as shown in Figure 18.

(2) Modified low-voltage Field Emission Corporation Fexitron with two image intensifiers, as shown in Figure 18 with a programable sequence of 3 or more pulses.

(3) High-voltage Field Emission Corporation Fexitron Model (300 kv or greater) activating photographic film placed directly behind the soil bin. (The image intensifiers could be used with this system whereby the image on the output screen of the image intensifier could be photographed with a 16- or 35-mm camera.)

(4) Use of an electron optical system such as the Cinelix (Holland) with the Radio Corporation of America two- or three-stage image intensifier.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions.

a. General.

From the pilot tests it can be concluded that soil is a severe X-ray-scattering medium. However, there is ample indication that this can be reduced to a tolerable extent by use of a lead mask that allows X rays to pass into the soil sample over the field of view only, and by use of an X-ray mesh in front of the film. The maximum density and thickness of soil that can be penetrated by the Zenith Multiple Flash X-Ray System is 5 inches of Ottawa sand at 112 pcf. More success was obtained with the Field Emission (300-kv) Fexitron by penetrating 8 inches of Ottawa sand at approximately the same density.

By using the 12-inch shock tube, the average range of density changes that might be expected in soil columns confined in test containers is 0.5 percent for dense sands to 5 percent for loose clay. This range is below the density change (greater than 5 percent) that must occur to be detected as a contrast difference by the Zenith Multiple Flash X-Ray System. Some of the best static X-ray techniques employed in flaw detection of weapon components cannot distinguish density changes of less than 2 percent; consequently, the usefulness of X rays in detecting dynamic density changes must be confined to failure-mode studies where density changes of 5 to 15 percent are common.

b. Zenith Multiple Flash X-Ray System.

Quantitative data have not been obtained in the soil dynamics pilot studies with the Zenith Multiple Flash X-Ray System. However, the experimental data obtained with this system, though qualitative, allow some conclusions to be drawn about the system's capabilities as well as its feasibility as a tool for measurement of dynamic soil. The conclusions are as follows:

(1) It is evident from the tests that the X-ray intensity per pulse is not adequate to study soil samples over 5 inches thick.

(2) There are undesirable limitations on the model size and soil sample density largely because of inadequate X-ray intensity.

(3) Considerable geometric distortion, vignetting, and a large portion of the field of view are lost because of the 8-inch-diameter image

intensifier being used; however, vastly improved image intensifiers are now on the market.

(4) Where soil movement or particle velocities are under 100 fps, the shadow-edge smearing is about 1.2 mils. In comparison, this decreases the resolution far less than the edge unsharpness produced by scattering.

(5) The technique for producing eight frames of 35-mm film is good; however, frame rates to 10,000 per second are desirable to resolve the interaction effects caused by the leading edge of a stress wave with an object embedded in soil.

(6) The incorporation of an image intensifier makes it possible to photograph the object X-rayed on 16- or 35-mm film, thereby eliminating a difficult film-transport problem. Because of the transport problem, one cannot take advantage of the resolution obtainable by placing the film directly behind the soil bin if more than one frame is required.

It was concluded that to increase the capability and reliability of the Zenith Multiple Flash X-Ray System to the point where it could be used for dynamic soil measurements would require the following action:

(a) Return the multiple flash X-ray system to the Zenith Research Corporation to determine and eliminate the high-voltage reflections in the X-ray-tube circuit which have been the cause of repeated malfunctions and erratic operation.

(b) Use the [illegible] 9-inch Dynascope, Model XS20-500/4-5 Image Intensifier with the Radio Corporation of America Two-Stage Image Intensifier, Model C70012, with magnetic focusing to provide an overall light-intensity gain of nearly 10^6 (Figs. 19, 20). Provide the necessary coupling optics between the output of the two-stage intensifier and the 35-mm camera.

(7) The X-ray tube in this system appears to change its impedance as a function of the total number of times it has been pulsed; this results in voltage reflections back into the system.

The above modifications would provide a system with the same resolution (1.5 ℓp/mm) and the same pulse-repetition rates as before; however,

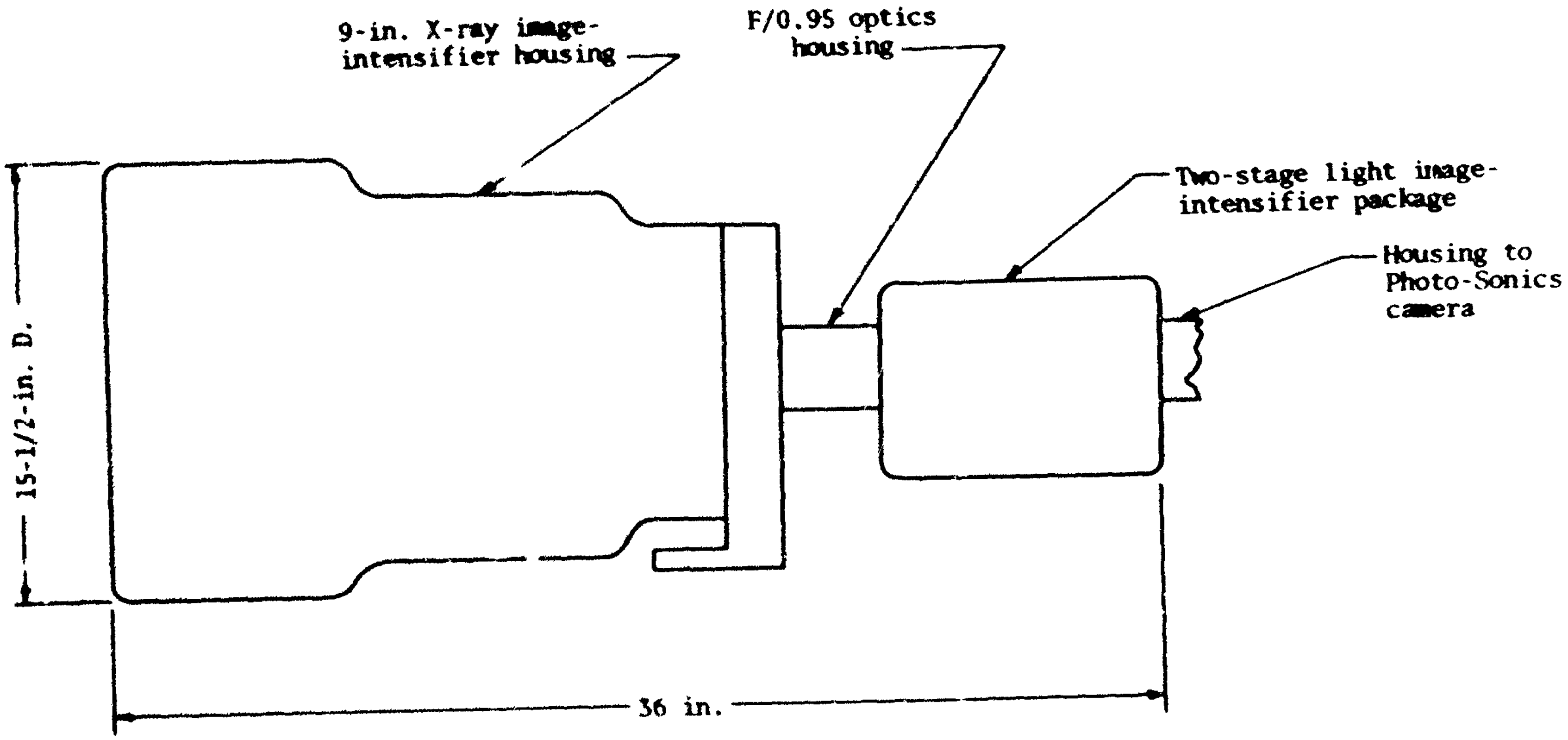


Figure 19. Image intensifiers in tandem

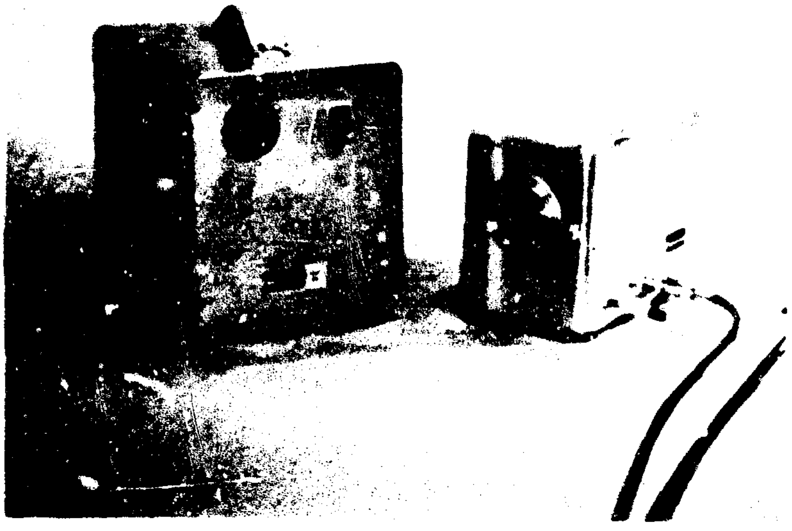


Figure 20. Two-stage image intensifier with permanent magnet-focusing and power supply

the system intensity gain will be two to three orders of magnitude greater, and the vignetting will be greatly reduced. This would allow the X-ray system to be operated with lower anode voltages and result in lower intensity and a shifting of the white X-ray spectrum to the long wavelengths. Furthermore, scattering unsharpness could also be reduced to adding lead screens, filters, and masks.

c. Field Emission Corporation Flash X-Ray System.

Four different radiographs were taken with a single-pulse Field Emission (300-kv) Flash X-Ray System of lead pellets positioned throughout an 8-inch-wide soil bin filled with Ottawa sand. The X rays successfully penetrated the 8 inches of Ottawa sand, and the radiograph taken of the embedded pellets was sharp and showed good contrast. Based on these results alone, it can be concluded that this system can be used successfully for a number of the previously mentioned dynamic soil tests.

It can be further concluded that the system has the potential for making dynamic soil measurements because of the following features:

(1) It is simple, easy to operate, and highly reliable.

(2) Its building-block design provides considerable flexibility. (It is possible to start with a single-pulse unit and progressively add as many pulses as required. The feasibility of a six-pulse system has been demonstrated.)

(3) It has an extremely short pulse width so that radiograph smearing is no problem even for object movements as high as 10,000 fps.

(4) It has a programable pulse-repetition rate, 10^5 pps for a single-tube X ray, 10^6 pps for a multiple X-ray system.

The radiographs were taken by placing film directly behind the soil bin. This gives maximum geometric resolution. It is concluded that with the use of an image intensifier and a 35-mm camera, the resolution should be the same as that obtained with the Zenith Multiple Flash X-Ray System.

2. Recommendations.

a. Basic Field Emission System.

A comparison of the two flash X-ray systems shows that the Field Emission Corporation Fexitron (300-kv) Flash X-Ray has the greater penetration capability and flexibility and appears to be more suitable for dynamic soil measurements. Flexibility is contained in its controllable pulse-repetition rate,

remote operation of the X-ray tube (up to 60 feet from the power unit), multiple-tube X-ray operation, and the capability of adding pulsers (six, possibly more) to the basic unit. It is, therefore, recommended that the basic *single*, 18-nsec pulse, 300-kv system be obtained to do the following:

(1) Conduct a series of tests on buried objects and models on soil-bin-boundary effects and on the physical changes of soil stress and motion gages under static and dynamic loads.

(2) Determine the maximum usable depth of penetration of X rays in soil and silt.

(3) Determine the maximum resolution obtainable from a test object based on its relative position in the soil bin by varying the soil and the material of the test object and by using filter, mask, lead screen, and special types of X-ray film.

(4) If it is necessary to include an image intensifier in the system, determine the maximum resolution obtainable with the 16- or 35-mm camera used with the image intensifier. Also, determine the advantages, for example, when Kodak Royal Blue film is positioned directly behind the soil bin.

(5) Determine the minimum detectable density variation of soil, possibly in stratified layers.

(6) Determine the reliability of the system by monitoring its performance and the time required for servicing and replacement of components. If, after the tests, the feasibility and practicality of the single-pulse X-ray system has been adequately demonstrated, then it should be expanded to a six-pulse system having variable pulse-repetition capability with a maximum rate of 100,000 pps. Such an X-ray system should be capable of radiographing the interaction of the leading edge of the stress wave with models buried in soil.

b. Other Available X-Ray Systems.

Available equipment should be investigated to determine if any other X-ray unit in combination with image intensifiers and other equipment would yield a more optimum system for measurements in soil. Of major importance would be the selection of equipment to reduce the effects of scattering by soil.

c. New Concepts and Techniques.

Improvement of present concepts and techniques should also be investigated. For example, the advantage of a 600- or 2,000-kv single-pulse

X-ray system over a 300-kv system may be significant enough in penetrability alone to warrant its use in specific tests.

The feasibility of the application of radioactive isotopes to dynamic soil measurements should also be investigated further. The gamma-ray energies of some of the more important gamma-ray-emitting sources range from 75 Kev to 2.8 Mev. Cobalt 60 has a half life of 5.22 years and gamma-ray energies of 1.2 and 1.3 Mev. Studies should involve placement of isotopes in soil, exposure times, safe handling, scattering, and absorption.

The use of the Mossbauer effect with the gamma-ray-emitting sources to show the movement of test objects in soil is one of the areas warranting further research. It should consist of a feasibility study of the application of the Doppler shifting of the photon, by rapidly moving the test object (photon receiver), to the problem of measurement in dynamic soil.

d. Mev X-Ray Systems.

Experiments have demonstrated that a field-emission-type X-ray system is capable of penetrating 8 inches of Ottawa sand. Although this penetrability is sufficient for certain dynamic soil tests, it would be advantageous to be able to penetrate 10 to 20 inches of Ottawa sand. This would allow placing larger models in the soil bin which, in turn, would help reduce the effects of the side walls of the soil bin. High-penetrability requirements call for X-ray systems in the million-electron-volt class. Such X-ray systems are commercially available. For example, Field Emission Corporation X-Ray Systems are available in the 2-Mev range, the Betatron can produce 10- to 20-Mev X rays (Allis Chalmers and General Electric models), and the linear accelerator can produce highly intense X rays in excess of 10 Mev.

All of these high-intensity X-ray systems are manufactured for practical, or commercial, applications and are available in relatively small units (200 to 300 cubic feet).

Application and use of such high-intensity X-ray systems are areas that heretofore have not been carefully considered; they warrant further study, particularly in light of the need and desirability of using thick soil samples.

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13. ABSTRACT

This research was conducted to assess the utility of flash X-ray techniques in soil dynamics studies. Areas where these techniques should be successful, their limitations, and the type of information to be expected from them are discussed. Static and dynamic tests were conducted on soil samples of various thicknesses and densities, and on buried structures of various dimensions using the Zenith Radio Research Corporation Model 1454 Flash X-Ray System. Initial tests defined the proper techniques to record pictures under optimum conditions of exposure, scatter elimination, and sample size and density. Final tests showed that qualitative information could be collected on certain loose soils and that interaction problems could be designed to yield large deformations. Soil thicknesses of over 5 inches could not be penetrated satisfactorily by the Zenith Flash X-Ray System. However, recent preliminary tests (June 1965) with a 300-kv Field Emission Corporation field-emission X ray were made through 8 inches of soil. It was concluded (1) that direct recording on film instead of using an image intensifier provides better contrast, field of view, and resolution, but problems of intensity and film transportation are great; (2) that more refined techniques and improvements are needed to collect quantitative information; and (3) that the inadequate state-of-the-art in multiple flash X rays at the time of this research limited their utility in soil dynamics. Further investigation is recommended based on recent and significant developments in field-emission X-ray-type systems.

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Intensifier						
Resolution						
Field emission						
Whole field technique						
Density change resolution						
Repetition pulse rate						

INSTRUCTIONS

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